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LANGLEY RESEARCH CENTER

LONG RANGE NOISE REDUCTION RESEARCH PLAN

By Staff of the Acoustics Branch, Loads Division

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STATUS AND TRENDS OF NOISE REDUCTION TECHNOLOGY AND RESEARCH GOALS

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This document represents an effort to summarize and evaluate the-state-of-the-art and to indicate the direction of future research relative to the reduction of aircraft noise. In performing this task, a number of organizations and individuals were visited who unstintingly gave up valuable time to discuss the various problem areas. A listing of those organizations and individuals is given below:

The Boeing Company, Seattle, Wash.

Mr. John Little, et al

McDonnell Douglas Corp., Long Beach, Calif.

Mr. Alan Marsh

Mr. Robert Pendley

Hamilton Standard, East Hartford, Conn.

Mr. George Rosen

Mr. Frederick Metzger

Pratt and Whitney Aircraft, East Hartford, Conn.

Mr. J. D. Kester

Mr. Thomas Sofrin

Sikorsky Aircraft, Stratford, Conn.

Mr. Ronald Schlegel

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CHAPTER 1

INTRODUCTION

The annoyance caused by noise on the community has become one of the more important environmental problems--for aircraft, in particular. The CARD study, ref. 1, concluded that the reduction of noise caused by aircraft during take off and landing should receive the highest priority. In response to this requirement, a joint office has been formed by the Department of Transportation and the National Aeronautics and Space Administration, whose function is to coordinate all governmental research and development leading to quiet commercial aircraft.

The Langley Research Center has been involved for many years in research of a basic and applied nature in effecting noise reduction applicable to aircraft operations. As part of the total national effort, Langley Research Center has recently made a detailed study of the state-of-the-art of the various discipline areas as a background to formulating a detailed research plan. The present document is essentially a summary of the state-of-the-art, but also, a certain amount of background material has been included. The report is aimed at the technical reader who may not have in-depth knowledge of noise technology.

The solution of the noise annoyance problem will require a multi-faceted approach--not only must the source of the noise be reduced, but many techniques of noise alleviation must be sought and used, such as proper use of land around airports, scheduling of aircraft, and operational techniques. Aircraft design philosophy must of necessity change; acceptance of some performance penalties for noise reduction will be required. Overriding all of these noise reduction techniques is aircraft safety--installation of additional hardware such as duct lining, for instance, must be qualified from the standpoint of sonic fatigue. Changes in operational techniques such as landing at a higher approach angle must be within the pilot's capability to land safely in adverse weather.

The paper is divided into a number of chapters--Chapter 2 is concerned with noise reduction goals, Chapter 3 contains a review of the present and future air transportation systems, Chapter 4 is involved in a discussion of the state-of-the-art for 8 discipline areas. These areas are grouped into three categories, (1) source of noise, (2) propagation, and (3) response. Under the source of noise, the topics are: jet exhaust, airflow-surface interaction, rotating blades, sonic boom. Under propagation, we shall consider duct acoustics and propagation and operations. Under the response subject, we shall treat the flight structure and human response. The final chapter summarizes the more critical areas in each of the 8 discipline areas.

CHAPTER 2

RESEARCH NOISE GOALS

A desirable goal for aircraft noise alleviation research is to reduce the noise levels to the ambient levels existing in the community, which of course, will vary depending on the type of community: residential, manufacturing, etc. A rate of decrease of noise levels of 10 EPNdB per decade was suggested in the CARD study. The Federal Air Regulation, FAR-36, effective December 1, 1971, is the regulation which sets the noise levels for various CTOL aircraft and the regulation is shown on figure 1 for approach noise and figure 2 for take off noise where EPNdB is plotted against maximum gross weight. Noise from various aircraft is shown on this plot relative to the FAR-36 requirement. Also, the CARD goal of 1981 is shown and, finally, a long range goal is indicated. As can be seen, most of the fleet of commercial aircraft are above the FAR-36 requirement. Two new aircraft, the DC-10 and the Boeing 747, are both within the limits. We can make several observations from this figure as follows:

(1) The annoyance problem at the present time results from the operation of the current fleet of older aircraft and many of these aircraft will be flying for at least the next ten years. A retrofit program is necessary if these noise levels are to be reduced to the FAR-36 limit.

(2) Present technology developed over the last several years is adequate to accomplish this reduction. The major problem is economic--how much will it cost and who will pay for it?

(3) The present generation of new aircraft, the DC-10 and the 747, have already used the latest technology and the DC-10 is about 20 dB below

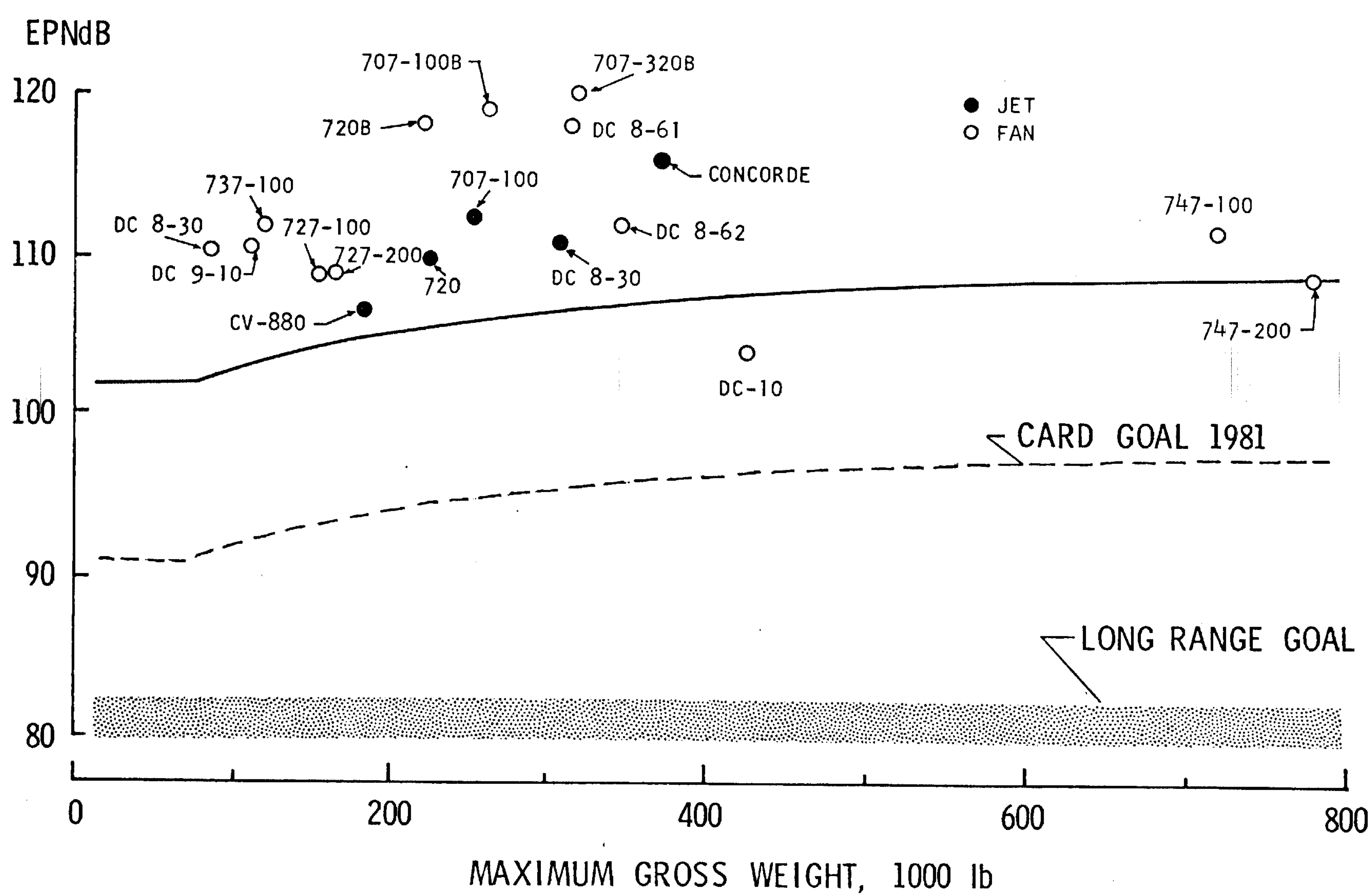


Fig. 1 APPROACH NOISE (1 n.mi. FROM THRESHOLD OF RUNWAY)

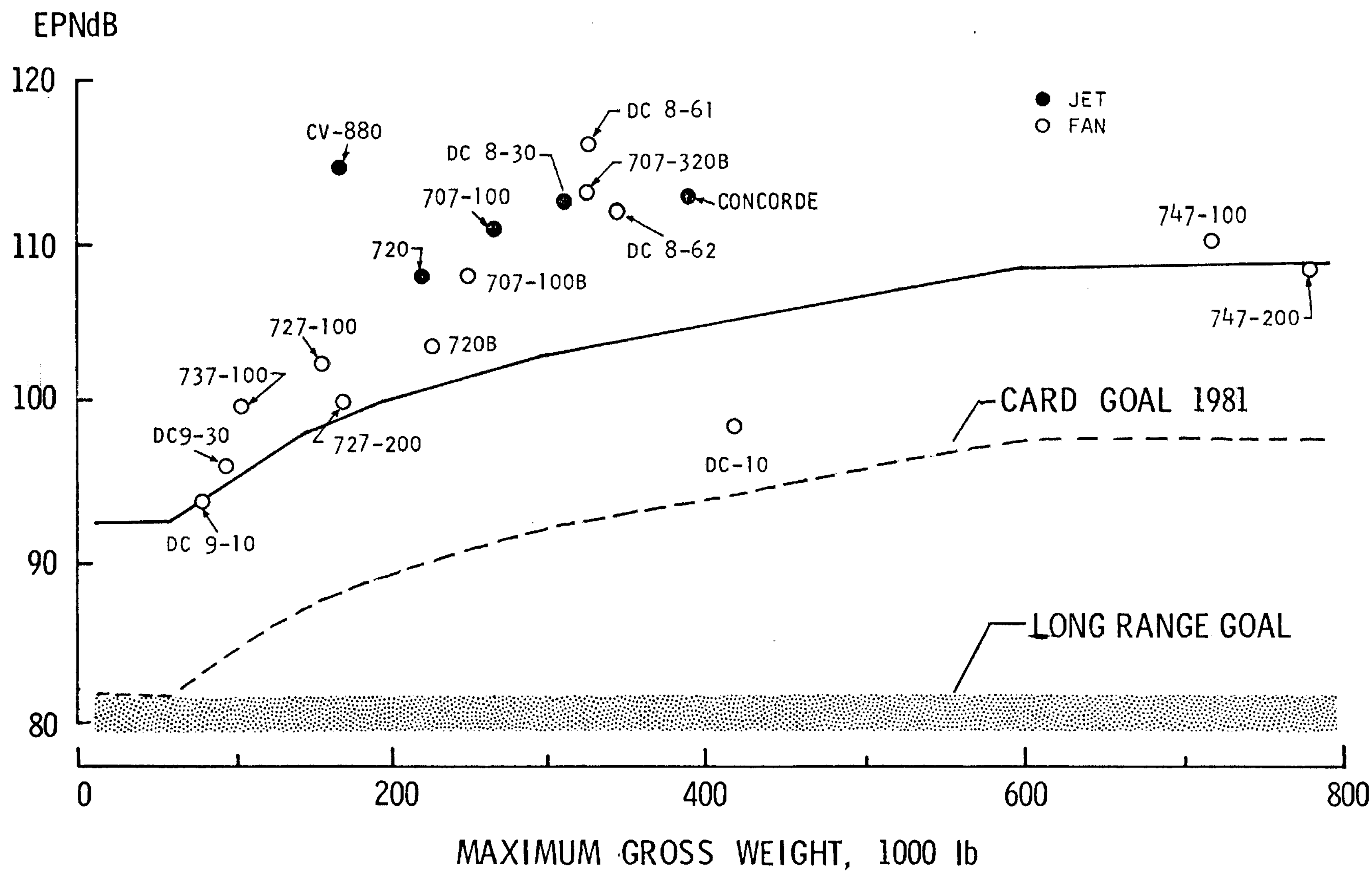


Fig. 2 TAKE-OFF NOISE (3.5 n.mi. FROM BRAKE RELEASE)

the noise of the worst case of the older aircraft. Thus, we have achieved about a 10 dB reduction per decade from the noisiest of the old aircraft to the latest operational aircraft.

(4) The attainment of the CARD goal by 1981 for new aircraft does not appear to be an unsurmountable technical problem.

(5) The major thrust of research for the next several years should be directed at providing the technology to reduce the noise from the DC-10 level to the level we have labeled as the "long range goal." This goal is of course open to debate, the level indicated on the figure is based on past experience which separates complaints from noncomplaints in a quiet neighborhood, but further research is needed to better define an ultimate goal.

(6) The Federal Air Regulation 36 applies only to CTOL. Similar laws will be on the books for STOL, VTOL, and general aviation and we will have to direct our attention to these aircraft and reduce the noise levels to some similar ultimate goals.

CHAPTER 3

PRESENT AND FUTURE TRANSPORTATION SYSTEMS

In effecting a research program that will be viable over a long period of time, a projection into the possible future aircraft and propulsion systems is necessary. This chapter is concerned with a discussion of the various aircraft and a projection into the future as it affects the overall noise picture. We shall divide the aircraft into two general categories: general aviation and commercial aviation.

General Aviation

A projection of aircraft by type was given in reference 2 and is reproduced here in figure 3. As can be seen, the number of propeller-driven aircraft is projected to 150,000 machines by 1985. Although the small propeller aircraft does not rate as a major noise source at the present time, with a multiplication by a factor of 4, in 1985 the use of small, close-in airports could result in an annoyance problem. The number of turbojet or turbofan aircraft is projected to be larger than the present commercial fleet. At the present time, some of the general aviation fleet are very noisy and exceed the FAR-36 requirement for CTOL operation.

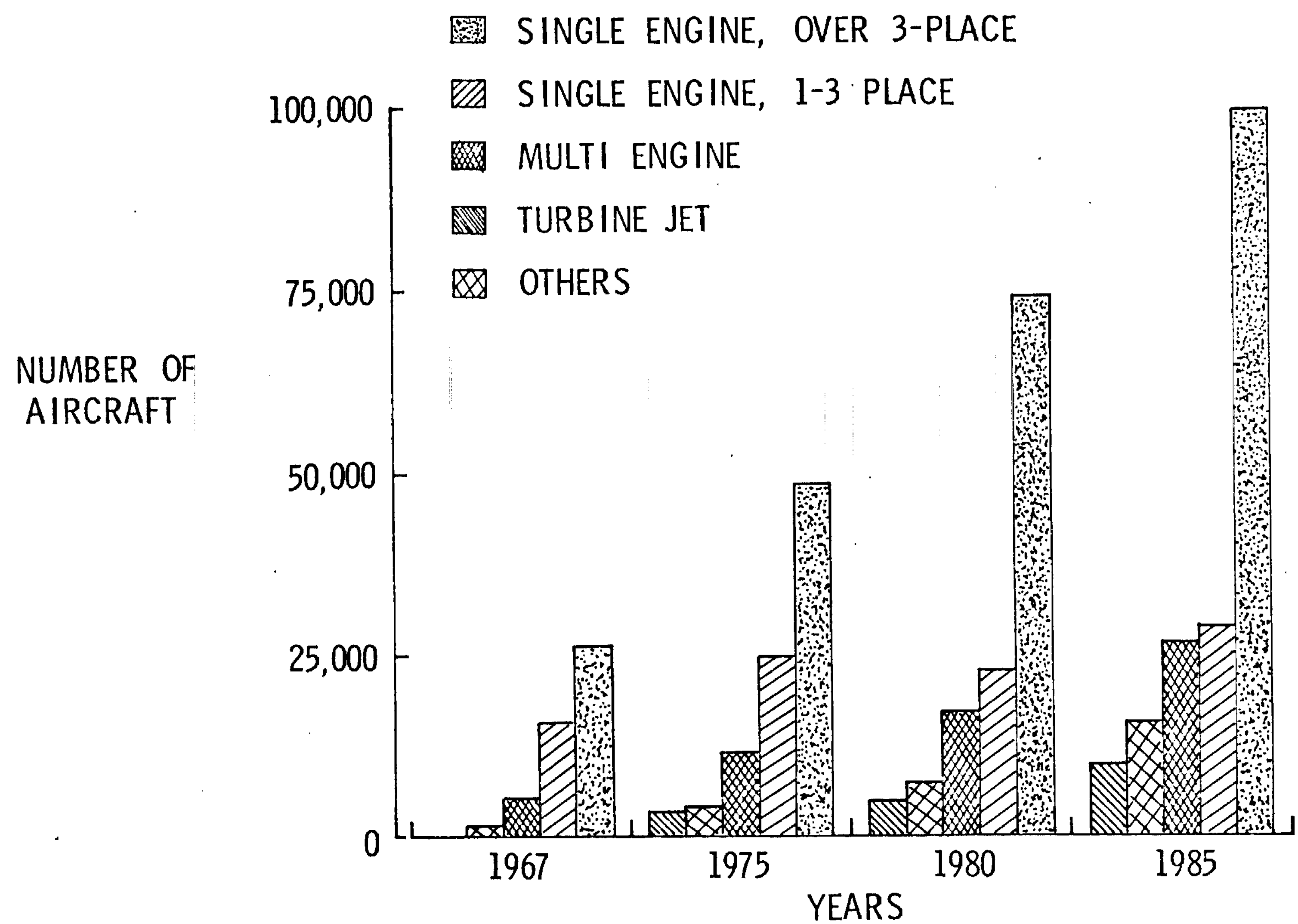


Fig. 3 PROJECTION OF GENERAL AVIATION AIRCRAFT

Others are relatively quiet and fall below the requirements. Those that fall below the present CTOL regulation are propelled by turbofan engines.

There seems to be no projection for the use of helicopter or autogyro-type machines for general aviation, although a number are in use for police and traffic reporting and management, crop dusting, pipeline surveillance, etc. and community noise annoyance has been reported for some of the operations.

Unless a breakthrough occurs in the cost of turbine-power engines, the propeller/reciprocating engine will be the backbone of the fleet of private flyers for many years. Technology is in hand to make a considerable reduction in the noise of propeller/reciprocating engines but, of course, at an increase in initial and operating costs. For instance, the installation of exhaust mufflers and reduced propeller tip speed by use of a gear reducer could make a considerable reduction in noise. It is surprising that the operators of these vehicles do not insist on a quieter airplane due to the very high level of cabin noise, which in some instances is as high as 110 dB, and is therefore sufficiently high that permanent ear damage is possible. It is suggested that the technology now available be brought to the attention of the general aviation industry--illustrating how, with minimum cost, the small propeller/reciprocating engine aircraft could be quieted, both for the benefit of the occupant and the community. At the present time, there is no Federal regulation specifying the maximum noise level of an aircraft weighing under 12,000 lb., although indications point to the day when a law may be on the books.

Commercial Aircraft

Subsonic CTOL - There are about 3,000 subsonic commercial aircraft operating in the United States today. Almost all of the aircraft are of the conventional type (CTOL) of which the DC-8, 707, and 727 comprise the largest number, and increasing numbers of DC-9's and 737's are also being placed into service. The 747, DC-10, and Lockheed L1011 comprise the latest addition to the fleet. To obtain noise reduction of the present fleet, some retrofitting will be necessary. Retrofitting can range from the installation of duct lining material in the inlet cowl and in the exhaust pipe as a minimum on existing engines--with major engine modifications, such as the development of a new fan stage, or to a completely new engine. The next generation of subsonic CTOL will probably appear very similar to the present airplanes--such advances as the use of composite materials, supercritical wing resulting in higher cruise speeds, etc., will probably be used. The impact on noise, however, will be small. The major improvement in noise abatement will have to come through advanced engine design and operating procedures.

SST - The United States SST was not supported by Congress, based on the possible environmental impact as well as economic considerations. Of environmental problems the reduction of sideline noise was not solved. Also, the sonic boom over pressure was excessive, although restriction to over-water flight certainly should have alleviated concern due to the sonic boom. During landing, the inlet would have been choked and very little noise would have emanated from the compressors. During take off the thrust-to-weight ratio was high and the noise at the 3.5 n.mi. point would have been relatively low due to the altitude as well as a programed power cutback. Thus, the sideline noise appeared to be the major problem. Boeing had initiated a program to quiet the jet noise by the use of multitubes in conjunction with an ejector. The British/French Concorde has the same problem but they have not approached the problem in the same manner. By changing the geometry of the jet cross section by the use of partially deflected clamshell thrust reversers, they hoped to change the noise pattern such that the sideline noise level would be within acceptable limits.

With the demise of the U.S. SST, an opportunity is now afforded to utilize the latest technology, both for airplane configuration as well as new engine cycles. From the standpoint of cruise, the arrow wing appears to be the more promising configuration since it has a higher L/D than the delta wing, figure 4 (ref. 3). There is now the opportunity to develop a quieter engine than previously planned. The original U. S. SST engine was a turbojet with afterburning, as is the present Concorde engine. A new type engine cycle, which would not require afterburning, is felt to be necessary. One such engine is termed a variable cycle engine. Fundamentally, it operates as a low bypass ratio engine for take-off but as a turbojet at supersonic speeds, by operating gates that are open to create the low bypass for take-off and which close to create a true turbojet for supersonic flight. The fan stage, however, requires variable inlet guide vanes and rotor stages to maintain efficient flow. This engine would create less noise than the true turbojet due to lower jet exhaust velocity, and, from noise consideration alone, research should be pursued to support the development including the effect of a larger diameter engine on performance. In addition, this engine cycle has

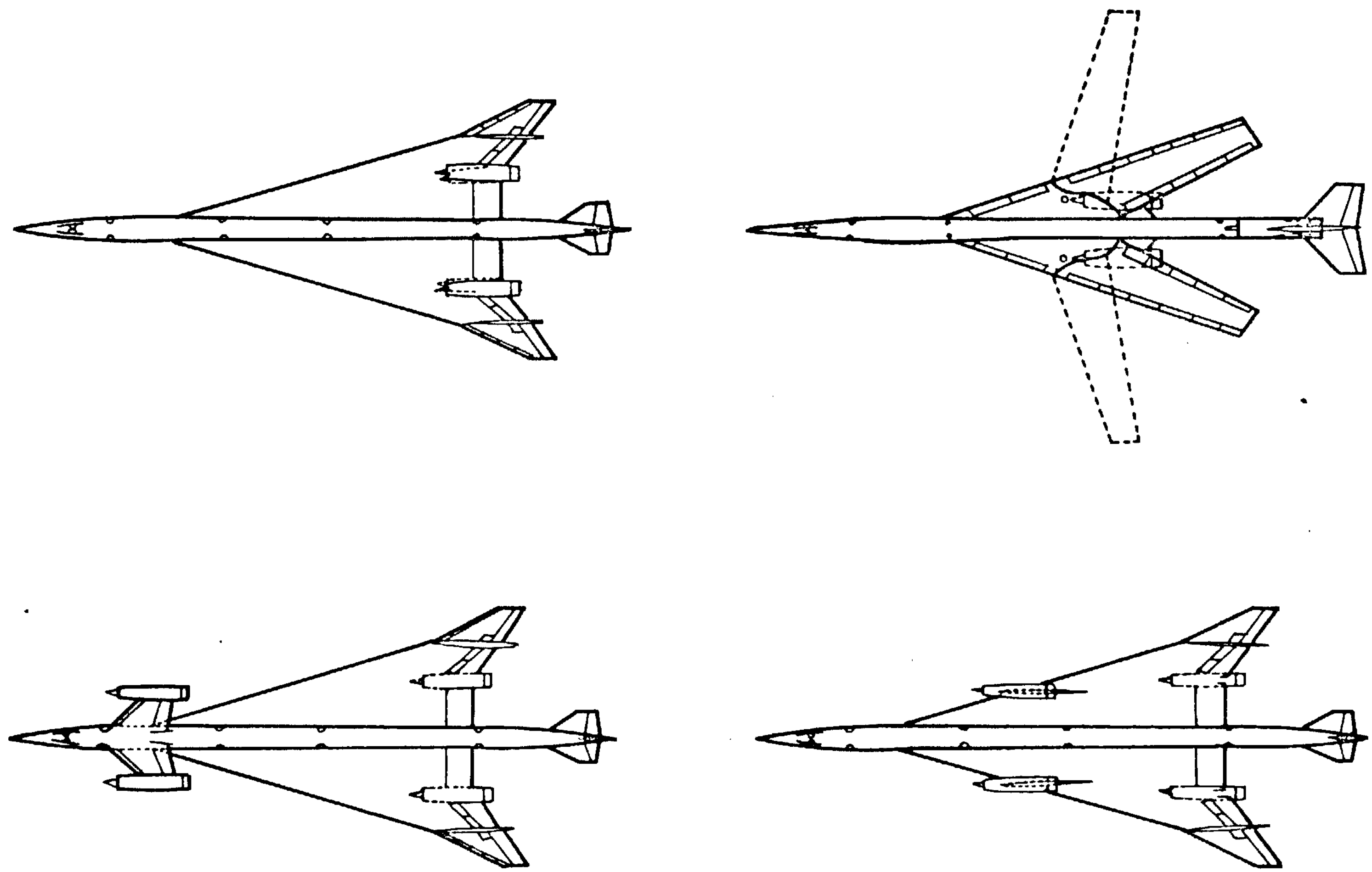


Fig. 4 ALTERNATE SECOND-GENERATION SST CONFIGURATIONS

lower fuel consumption than the comparable, equivalent thrust turbojet for subsonic operation.

STOL - The concept of a short take off and landing airplane (STOL) has been a dream for many years, yet the economics of the situation has not led to the development of a practical and usable 100 to 150 passenger STOL. The idea of locating an airport near a city center with a 2000-foot landing and take off strip has been advocated to help alleviate the long time required for passengers disembarking from a CTOL to reach the city center. Also, the STOL aircraft would be used between city centers within 500 miles. When a STOL port was proposed for Manhattan Island, to be located on the water front, the local inhabitants were able to stop the project in spite of the fact that the airline and local government authorities asserted that the noise from the port would not be as obtrusive as the levels already existing in the community.

At a recent AIAA panel discussion on STOL at the Eighth Annual Meeting and Technical Display, the panel generally agreed that an overall systems study of STOL has not been made and that such a study, taking into account all important factors, should be made. In a statement prepared by the STOL panel, the following introductory statement was made:
"We know that many different STOL, VTOL, and V/STOL aircraft can be built and flown. Many have been during the past 15 or 20 years, and some have managed to survive without crashing. But in spite of this we still have to say 'so what, nobody is using them.'"

One of the reasons for a systems study of the STOL concept relative to noise abatement is, for instance, the apparent decision which has already been made that an STOL should operate at $M \approx 0.8$. This requirement immediately discounts the prop/jet airplane since it cannot fly efficiently at such a high Mach number, in spite of the fact that the technology now exists to produce a quiet prop/jet STOL. Interestingly, the Ford Trimotor and DC-3 fall within the present definition of an STOL. In other words, the airlines really want a combined STOL/CTOL since the average distance the present CTOL operates is about 500 miles.

A generally accepted noise goal of 95 PNdB at 500 feet has evolved. It is understood that this level was suggested by a London Airport group and has become widely accepted. It is felt that this noise level should be reexamined in the light of recent airport surveys; for instance, perhaps the specified noise level should be established at the perimeter of the airport property rather than at some arbitrary location such as 500 feet. Therefore, a systems study should include the recommended minimum size and shape of an STOL airport.

The present trend in the United States is toward a rather conventional aircraft, but with the use of power assist during take off. Some of the more prevalent ideas at present are depicted in figure 5. These consist of (1) the internally blown jet flap, (2) the augmentor wing, (3) the externally blown jet flap, and (4) the internally blown flow combined with upper surface blowing.

Of these four concepts, the internally blown flap may be the quietest system; however, it would require the development of a new high pressure ratio engine. The externally blown flap is the more favored configuration at the present time for two reasons: (1) the existence of a compatible

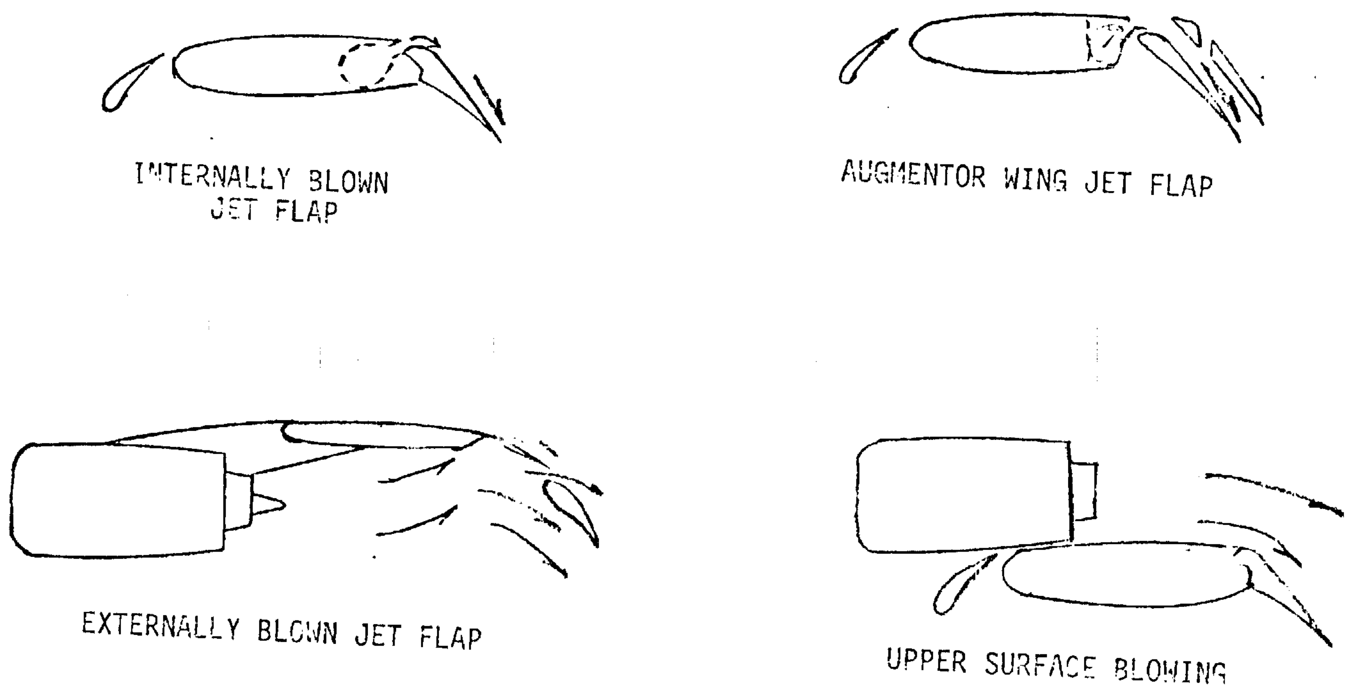


Fig. 5 JET FLAP CONCEPTS

engine and (2) the designers feel that more data have been obtained on the external flap concept and thus there is less technical risk. A major source of noise is, of course, the impingement of the jet on the flap system. Actually, very little is known concerning noise production of a jet striking an object, and this constitutes a primary area of noise research for STOL.

VTOL - The helicopter has been the most successful VTOL, although its commercial application has been limited and has required Government subsidization for continued operation. Militarily, the helicopter has been highly successful where performance and not economic consideration is the paramount criterion. However, in its present form, the helicopter is a noisy machine due to the unsteady flows associated with tip rotors, blade slap, tail rotor interaction, etc. An intensive research program is needed to define in greater detail the sources of the noise and method for alleviation.

Another VTOL aircraft has recently been put in operation--the Hawker-Siddeley Harrier. This is a subsonic fighter using direct thrust for vertical take off, with a transition to horizontal flight by thrust vectoring. This aircraft uses the Pegasus 101 fan-jet engine of 18,750 lb. thrust, and the operation of these aircraft is extremely noisy.

Numerous research VTOL have been produced; this includes the German Dornier DO-31 which uses a Pegasus engine for direct lift thrust. The Air Force XC-142, designed and constructed by Ling Temco Vought, was a tilt wing, prop-jet aircraft which was successfully flown but has not earned production status. Bell Aerospace Corporation produced the Navy

S-22, utilizing four ducted fans (T-58 by G.E.). The Army developed a series of VTOL, designated the VZ-2, VZ-4, and VZ-5, each utilizing different means of obtaining vertical thrust. None have been put into production.

All of these systems involve a rotating blade, either free or ducted. Research is needed to define the noise sources, particularly the broad-band type, to identify their origins and determine means of alleviation.

Propulsion Systems

The major source of aircraft noise is, of course, the propulsion system and most of the research effort in noise suppression will be centered in this area. The two overriding criteria in designing a propulsion system have been safety and efficiency. A third element must now be added; namely, a quiet propulsion system.

A summary of overall propulsion efficiency for various systems is given in figure 6, plotted against flight Mach number. For subsonic speeds, the turbo prop is the most efficient system, whereas the turbojet is the most efficient for application to the supersonic cruise airplane, with the by-pass turbofan engines lying in between. However, noise seems to vary inversely with propulsion efficiency, the turbojet being the noisiest, and the turboprop being the quietest.

There are two major problems connected with the propulsion system, (1) how to economically reduce the noise level of the existing fleet of subsonic airplanes and (2) how to effect large noise reductions for future propulsion systems.

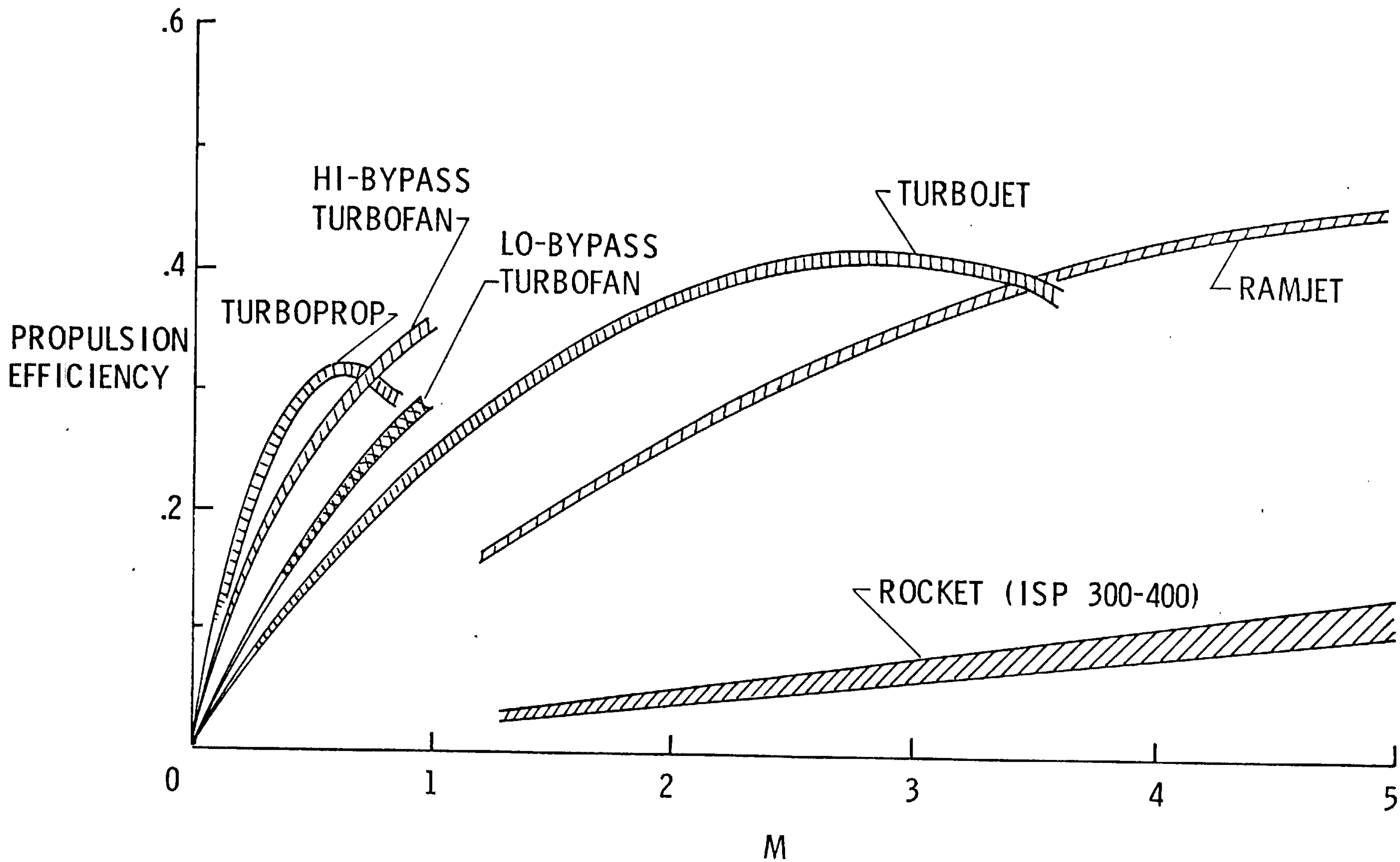


Fig. 6 OVERALL PROPULSION EFFICIENCY

With regard to the present engines, the fan noise can be reduced by the use of acoustic liners in the inlet cowl or by choking the inlet flow. Perhaps some multilobe/ejector concept may be used to reduce the jet exhaust noise. Other changes could be made which would involve new fan stages, but this step would be costly.

For future engines, it appears that research should be directed at the two ends of the spectrum, one engine for STOL and another for a future SST. For STOL application it appears a possible engine cycle that may be applicable is the high-bypass ratio fan engine. A plot of the engine spectrum is shown on figure 7, where the blade tip speed is plotted against fan pressure ratio. The JT9D is shown which represents the latest state-of-the-art for CTOL; the British M45S and French ASTAFAN II are shown in the middle of the range. The proposed Hamilton Standard low pressure engine is representative of the range of pressure ratio of 1.1 to 1.2 which has the potential for meeting the STOL standard of 95 PNdB at 500 ft. To obtain this low noise level, very careful attention has to be paid to the fan interaction with the exit guide vanes, to the acoustic treatment in the inlet and exhaust of the nozzle. Since the engine has a very large bypass ratio in the range of 15/1, the core engine exhaust noise will be very low and should not represent a significant noise source, although the impingement of the jet exhaust on the flaps will produce considerable noise.

For SST application, it would be desirable to develop a variable cycle engine, one that would operate subsonically as a low-bypass turbofan, and convert to a true turbojet for supersonic speed. Not only would the take off noise levels be lower, but an engine with higher propulsion

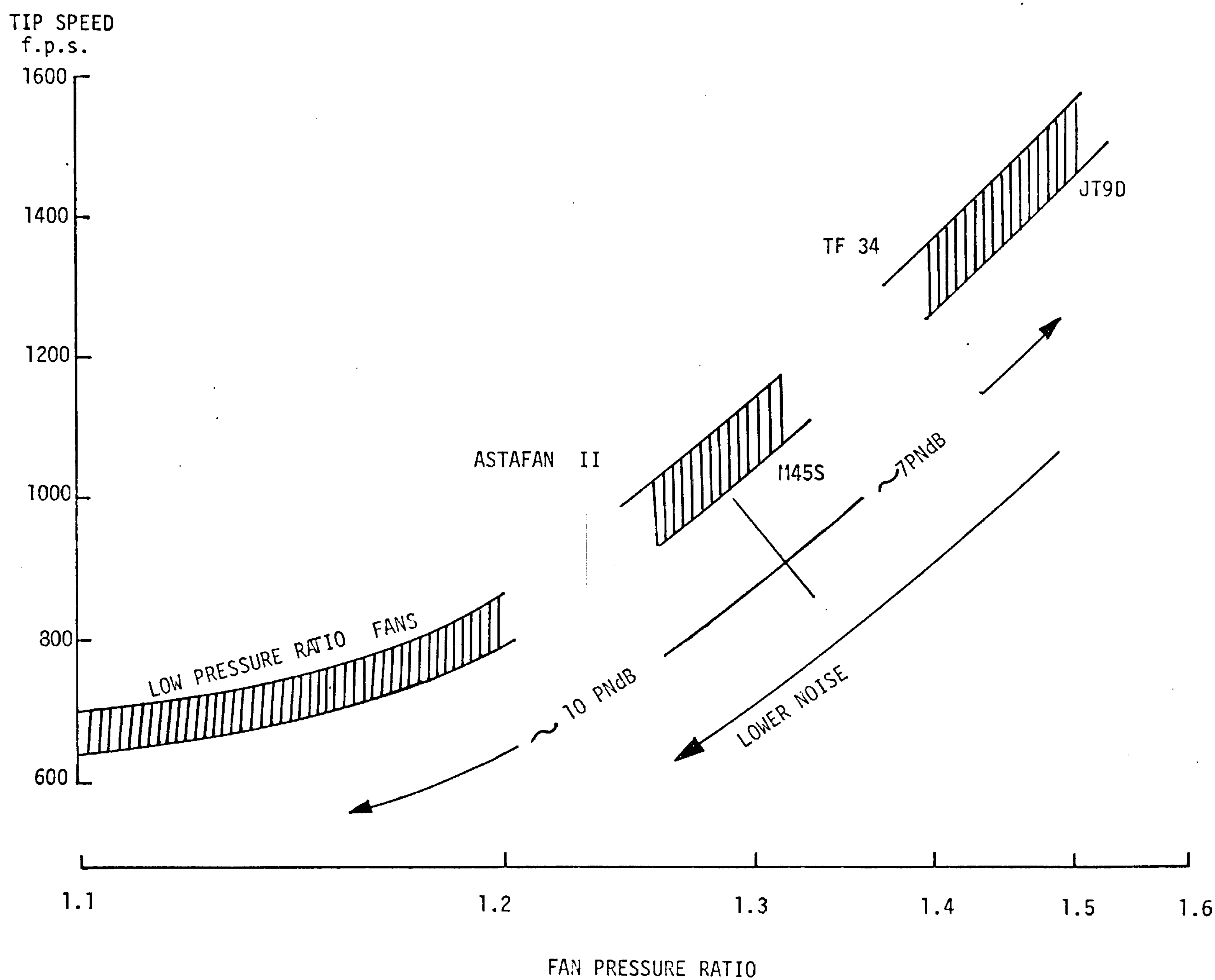


Fig. 7 FAN SPECTRUM

efficiency for the subsonic portion of the flight would be obtained. In additi- the engine would not require afterburning to obtain the required thrust, which is desirable since afterburning is a large noise source. The major problem in designing such an engine is the adjustment of the airflow into the engine for the two entirely different flight conditions. For instance, the by-pass air would have to be closed off with a door arrangement and the fan and stators would have to be adjustable when changed from the subsonic to the supersonic mode of operation.

CHAPTER 4

TECHNOLOGY STATUS AND TRENDS

In studying the aircraft noise alleviation problem from a technical viewpoint, it is convenient to organize the subject into three groups, (1) source noise, (2) propagation, and (3) response. Under each group we can then list various subgroups for discussion purposes as shown below:

SOURCE	PROPAGATION	RESPONSE
1. Jet Exhaust	5. Duct Acoustics	7. Structural Response
2. Airflow-Surface Interaction	6. Propagation & Operation	8. Human Response
3. Rotating Blades		
4. Sonic Boom		

For take off of a fixed wing aircraft, the propulsion system provides the major sources of noise, and the major sources are shown on figure 8. The noise emanating from the inlet arises mainly from the rotating fan as well as the interaction of the flow from these blades with the stator or stationary blades. Similarly, the noise from the fan discharge duct arises from the same source, but has imposed on it the fundamental jet exhaust noise. The noise emitted from the rear of the engine may be composed of several parts: (1) the noise arising from the mixing of the high speed jet with the surrounding lower velocity air, (2) internally created noise from the turbine, from combustion processes, or from turbulence created by bodies and struts in the flow, (3) and for supersonic flow, unstable shock waves may be a source of noise as

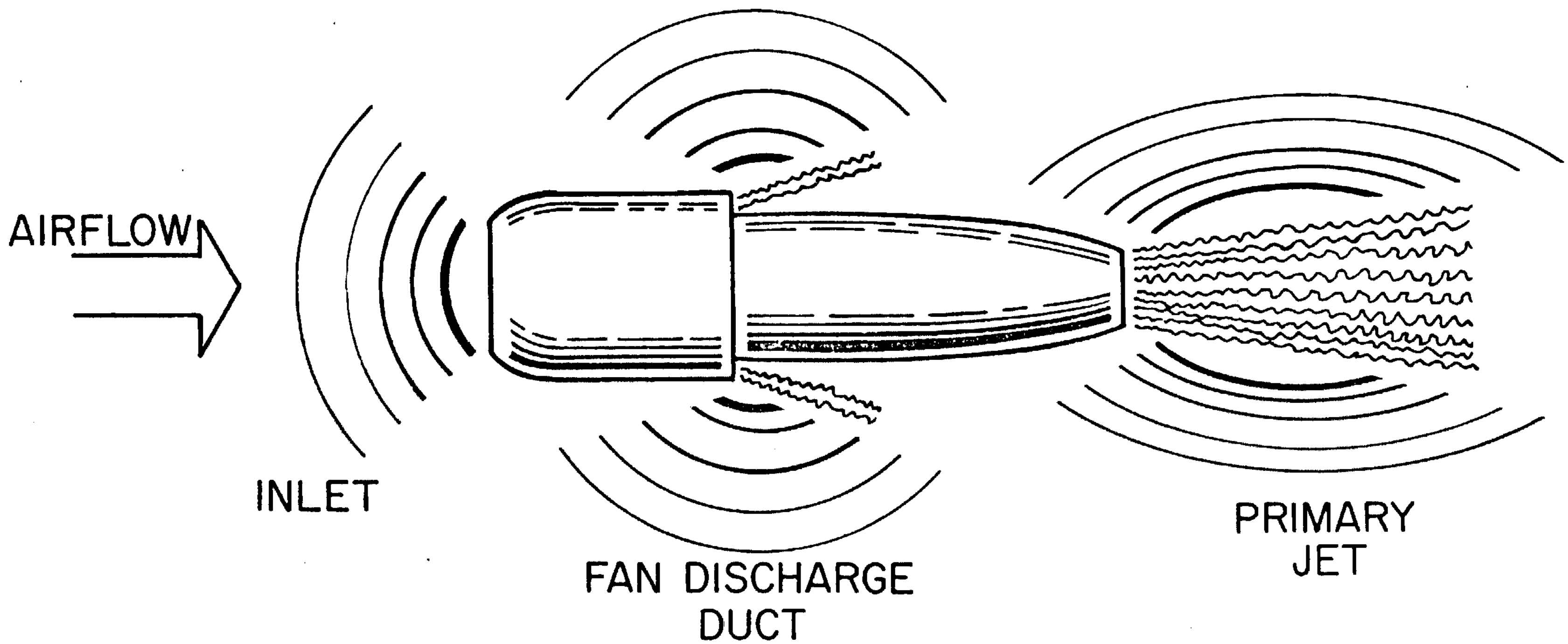


Fig. 8 THE SOURCES OF NOISE RADIATED FROM A TYPICAL TURBOFAN ENGINE

well as disturbances which travel at local supersonic speeds and induce a system of Mach waves.

Rotating blades, whether confined in an engine or operating in free space as a propeller or helicopter blade, have many sources of noise. Sonic boom from a supersonically flying aircraft is a source of impulsive noise and one of the main deterrents to the development of an SST.

Airflow-surface interaction arises when the flow strikes a fixed surface. Typical is the situation for the proposed STOL externally blown flap, in which the jet exhaust impinges on the flap system to create the additional lift needed for the short take off and landing.

The term "duct acoustics" refers to the propagation of sound through the engine ducts--i.e., the noise created by the rotating blades, for instance, which propagates through the confined inlet duct, and then is reflected and refracted at the termination of the duct through a rather complex physical process.

Propagation and Operation refers to aircraft operational techniques as well as how the noise created by the aircraft is transmitted through the air to the receiver.

The receiver may be the aircraft structure with concern for structural failure due to sonic fatigue, building structure as it responds to aircraft noise or the sonic boom and finally, and most important, the response of the human, which of course is the focal point and the main impetus for the attempt to reduce aircraft noise.

In the remaining portion of this chapter, we shall discuss each of the subgroups, defining the basic problem, the state-of-the-art, and finally a few remarks about the research required.

1 - JET EXHAUST NOISE

In spite of over 20 years of rather intensive research on the problem of jet exhaust noise suppression, there is still no effective jet noise suppressor on any commercial aircraft. Many ad hoc devices have been tested--they have failed either by causing too much thrust loss or are so large and heavy that the aircraft sustains a prohibitive performance penalty. Based on the large amount of testing that has been accomplished, it is possible to empirically predict the noise from a simple circular jet quite accurately--however, if one were to change the jet nozzle shape to a rectangular jet nozzle, for instance, there is no procedure available to predict the noise from this new configuration. Although ad hoc testing will have to continue, a more fundamental investigation into jet noise is required.

Some of the earliest experimental work was done by Hubbard and Lassiter (ref. 4), where it was shown experimentally that the jet noise varied as the jet velocity to the seventh power. At about the same time, Lighthill (ref. 5 and 6) developed the basic equation for subsonic jet noise and showed theoretically that the noise of a subsonic jet may arise from the shear flow (as modeled by quadrupoles) and that the noise was proportional to the jet velocity to the eighth power. Most of the later theoretical work has been based on Lighthill's original work, or can be shown to be equivalent to Lighthill's work. Figure 9 depicts the interrelationship of some of the theoretical developments, with the Lighthill theory as the central theme. Ribner (ref. 7) and Powell (ref. 8) (upper left) independently developed theories based on simple sources and their theories were found later to be equivalent to the Lighthill theory. Curle (ref. 9) and Ffowcs-Williams (ref. 10)

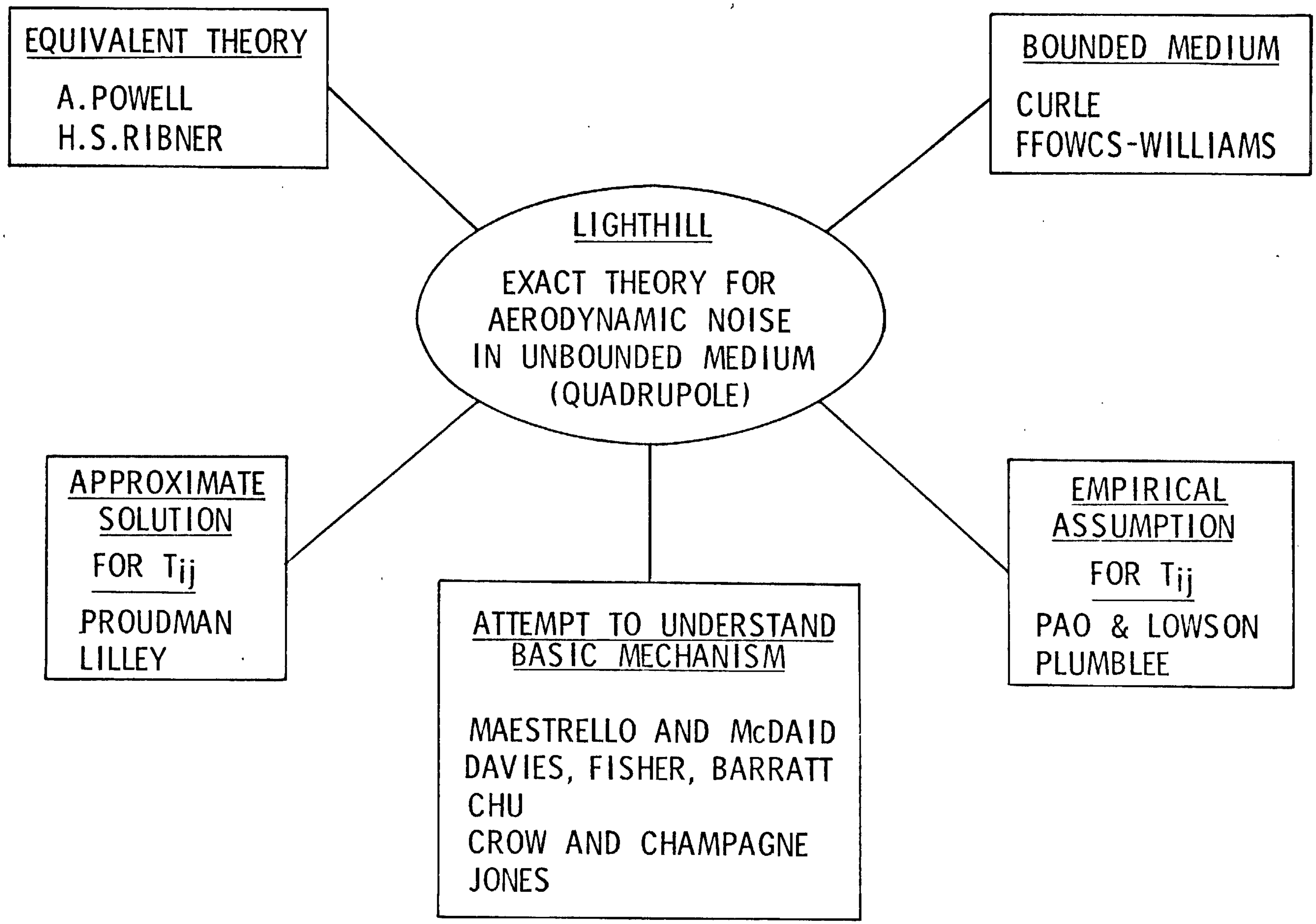


Fig. 9 SUBSONIC JET NOISE THEORY

(upper right box) extended the Lighthill theory to a bounded medium and established the theory for noise generation as a jet impinges on a solid boundary. Several solutions involving assumptions as to the form of the turbulence (lower left box) were obtained by Proudman (ref. 11) and Lilley (ref. 12). Empirical methods have been attempted and these are exemplified by the work of Pao and Lowson (ref. 13) and Plumblee (ref.14). The lower central box indicates the work of a number of investigators (ref. 15-19) in which each has attempted to define the ingredients of the Lighthill equation, essentially by the measurement of certain selected quantities. One of the problems with the use of the Lighthill equation is that it is very difficult to extract a certain phenomenon and examine its effect. Thus, alternate theoretical approaches are necessary so that one can, in a systematic manner, pull the jet noise problem apart, examine its pieces, and finally arrive at an understanding of where the noise is generated, the mechanism that generates the noise, the method of propagation of the noise through the jet to the outside of the jet with an ultimate goal of effecting a reduction in the generated and transmitted noise.

The term "jet exhaust noise" as used here refers to the total noise emanating from the exhaust of a jet engine. It combines two major sources of noise: (1) the noise due to the mixing of the jet with the surrounding air, and (2) the noise created inside the engine due to a number of sources such as internal turbulence, bodies, turbine blades, etc. Let us consider first the jet mixing noise.

Jet mixing noise -

Subsonic - The fundamental equation of noise production derived by Lighthill, and expanded by Curle and Ffowcs-Williams to include additional terms due to bodies and mass addition and force is given as

$$\frac{\partial^2 \rho}{\partial t^2} - a_0^2 \nabla^2 \rho = \frac{\partial Q(x,t)}{\partial t} - \frac{\partial F_i(x,t)}{\partial x_i} + \frac{\partial^2 T_{ij}}{\partial x_i \partial x_j}$$

where ρ is the density, a_o the speed of sound, $\partial Q/\partial t$ the rate of mass injection, F_i the applied force, and T_{ij} is defined as

$$T_{ij} = \underbrace{\rho v_i v_j}_{\text{Convection momentum}} + \underbrace{(P_{ij} - p\delta_{ij})}_{\text{Viscous stresses}} + \underbrace{(p - a_o^2 \rho)\,\delta_{ij}}_{\text{Heat conduction}}$$

Normally, the viscous stress term and the heat conduction terms are small compared to the momentum term, particularly for low-speed flows, so let us examine the momentum term. If we replace x_i by x,y,z and v_i by $U + u,v,w$ where U is the mean free stream velocity and u is the perturbation velocity, and expand the momentum term, we find quantities like

$$\frac{\partial U}{\partial y} \frac{\partial v}{\partial x}$$

The term $\partial U/\partial y$ represents a change in free-steam velocity in the direction normal to the jet, and $\partial v/\partial x$ is the change of the velocity v (which is in the y-direction) with x, the flow direction. The term $\partial U/\partial y$ represents a shearing action and is essentially a magnifier of a relatively small term $\partial v/\partial x$. Thus, we need a change in mean velocity along with stream turbulence velocity for noise generation.

The total acoustic power of a subsonic jet has been shown by Lighthill to vary with U_j^8, the formula being

$$I \propto \rho_0 U_j^8 a_0^{-5} l^2$$

and this law has been found to hold for the intermediate range of jet velocities.

Supersonic - No similar analysis has been found to apply to supersonic flow. The noise of supersonic jets may arise from shock oscillations, from disturbances which are convected supersonically and create measurable Mach waves, and finally by the subsonic portion of the jet which may exist 10 to 20 jet nozzle diameters downstream. Noise characteristics will also change if the stream is overexpanded or underexpanded at the nozzle exit. For this condition, the characteristics of the flow are highly dependent on the lip of the jet nozzle. Slight changes in the external pressure can induce movements of the shocks, and as a matter of fact, under certain conditions a feedback circuit between the nozzle lip and a downstream point can occur which will result in a screech. This phenomenon has actually occurred on production aircraft and has resulted in fatigue failure of nearby aircraft structures.

For a supersonic jet, the variation of total acoustic power has been found experimentally to vary between U_j^4 to U_j^6, depending on the particular exhaust conditions.

Internal noise - Theoretically, jet mixing noise varies with the jet velicity to the eighth power; therefore obvious way to reduce the jet noise is to reduce the velocity. For a practical engine, however, it has been found that for lower jet velocities, the noise does not follow the eighth power law but rather a fourth, fifth, or sixth power. A plot of the jet exhaust picture is given in figure 10 where overall noise is plotted against jet exhaust velocity. It has been postulated that the reason for the deviation at the low jet exhaust velocity is the internal noise generated in the engine and which emanates from the jet. There are a number of possible sources of internal noise as follows:

Turbulence

Struts and bodies

Combustion processes (hot spots)

Tones from turbine or upstream compressors

Structural vibration of blades or casing

Therefore, cleaning up the internal flow could have significant effects at the lower jet exhaust velocities.

Jet Exhaust Noise Reduction

In considering the jet exhaust noise reduction problem, there are fundamentally two paths which may be followed as depicted in figure 11. The two paths comprise (1) altering the source field or (2) altering the sound field. As stated previously the noise from a subsonic jet may vary as V^8, and any reduction in jet velocity will have a large effect on the noise produced. This reduction at supersonic jet speed is also applicable except that it follows the V^5 law. Increasing temperatures of a jet is known

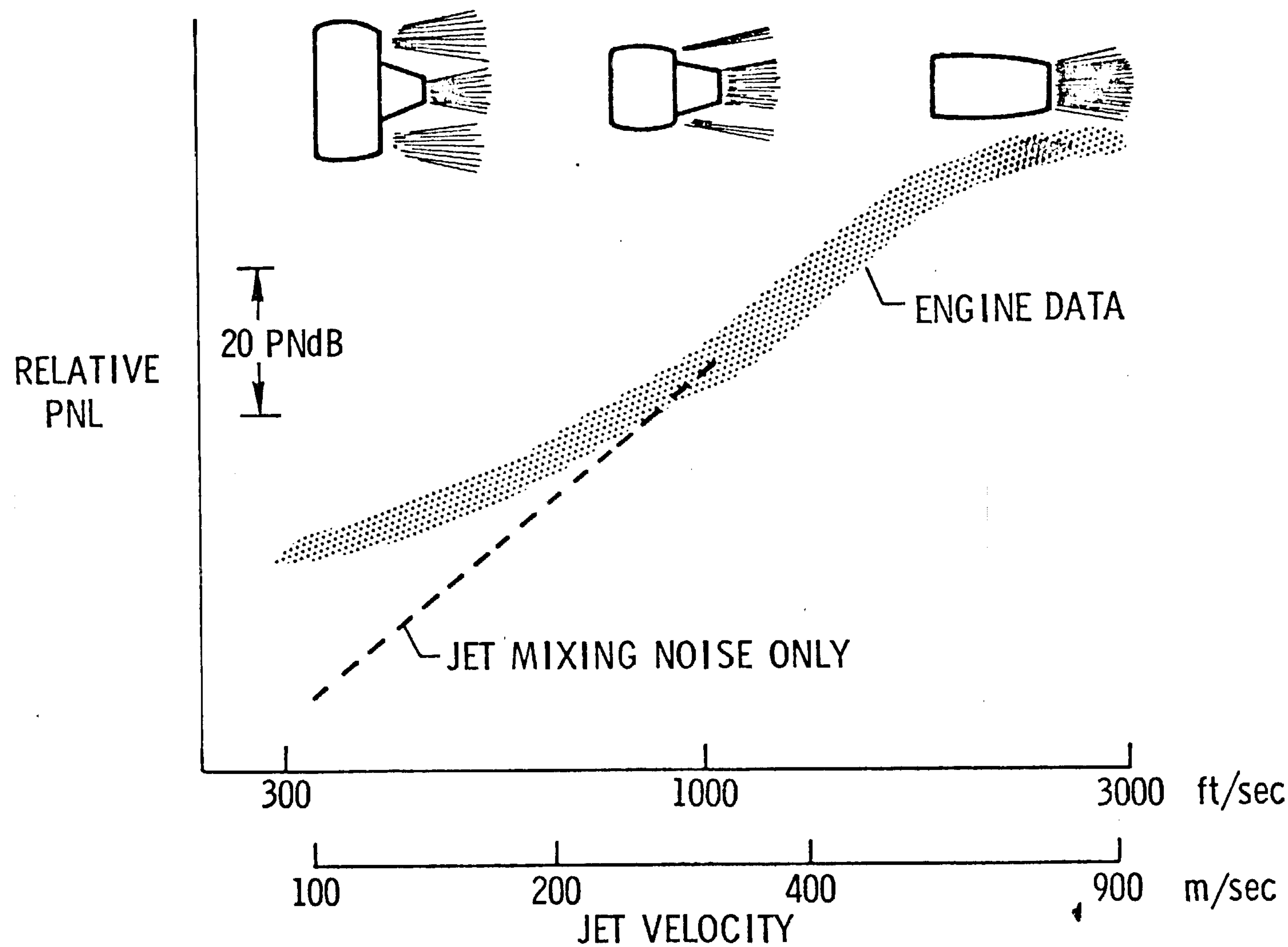


Fig. 10 EFFECTS OF JET EXHAUST VELOCITY

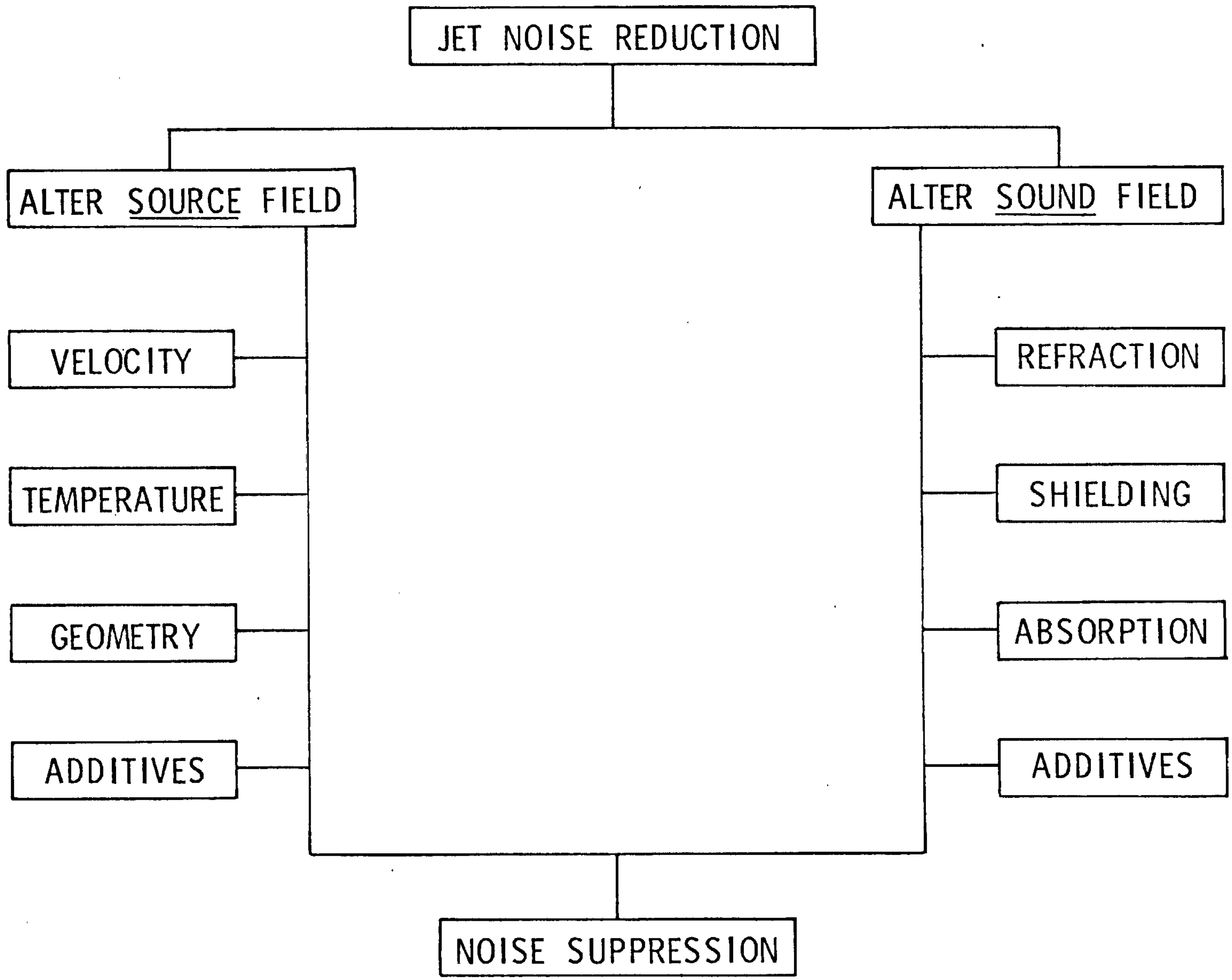


Fig. 11 JET NOISE REDUCTION

to reduce noise, although the reduction may not be of great practical importance for the normal range of jet temperatures. Geometry may be used in several ways--one is by using an asymmetrical jet to obtain a desired directivity of the noise which may be beneficial, or a jet may be divided into a large number of smaller jets, increasing the characteristic frequencies and shortening the noise producing section of the jet so that the jet may be surrounded by absorbing material in the form of an ejector. The use of additives is still in a basic research situation and it is an area requiring further research.

The second path essentially takes the noise already produced by the jet and tries to reduce or eliminate the noise. The sound waves may be refracted in a direction which would not impinge on the ground; for instance, by properly bending the waves by a velocity or temperature gradient. Shielding may be used, such as mounting the engine on top of the wing and, of course, the jet exhaust may be surrounded by an acoustic liner.

In order to accomplish the objectives of jet noise reduction, a fundamental research program is necessary. One of the problems in jet noise research is to determine what physical quantities must be measured. For instance, some quantities which should be measured during tests are:

(1) Mean and fluctuating velocities
(2) Mean and fluctuating temperatures
(3) Fluctuating pressure, near and far field
(4) Second order of velocity, temperature, and pressure fluctuation
(5) Fluctuations of jet interface (nature of jet boundary)

From these measurements, such quantities may be derived as

(1) Kinetic energy flux

(2) Role of the dissipation of kinetic energy as a noise source
(3) Rate of entrainment of the external flow
(4) Acoustic energy density

Many of the tests that have been made in studying jet noise have had a considerable amount of noise contamination in the jet before it exhausts to the atmosphere and this unknown quantity certainly clouds any generalized conclusions concerning jet noise. In performing a research program on jet noise, some measure of the internal noise should be given by the researcher for each test result, one such measure could be measurements of the coherency function between the internal pipe pressures and the far field pressures, which would indicate correlation between the internal and external noise fields. Perhaps another measurable quantity may be more meaningful, but it is felt that some attempt by the many researchers in jet noise should be made to agree on such a "standard" measure which would be reported along with each test result.

To summarize, it is felt that the critical issues for the solution of the jet noise problem involve:

(1) Determination of the origin and location and type of the noise source

(2) The propagation path of the noise through the jet

(3) The development of practical noise suppressors

Specifically, it is recommended that a fundamental research program, both theoretical as well as experimental, be initiated--starting with the simplest circular cold jets and progressing to hot jets, coaxial jets multijets, etc. In each of the steps of the program, the fundamental quantity listed in this section should be measured and a parallel theoretical development should be paced such that the theory precedes and guides the experiment. A detailed program is given in the following outline.

1 Jet Exhaust Noise

1.0 Review Literature on Jet Exhaust Noise and Publication of Summary Paper, Including an Evaluation and Critique

1.1 Fundamental Research in Jet Mixing - Subsonic and Supersonic (See page 4-8 for quantities to be measured)

1.11 Circular Jet

- 1.111 Cold
- 1.112 Hot

1.12 Parallel Jets

- 1.121 Shielding effect
- 1.122 Aerodynamic effect
- 1.123 Theoretical development

1.13 Coaxial Circular Jet

- 1.131 Variation of secondary to primary velocity and area ratios
- 1.132 Temperature
  - 1.1321 Hot primary - cold secondary
  - 1.1322 Cold primary - hot secondary
- 1.133 Variation of exit planes of secondary and primary
- 1.134 Develop theory for coaxial jets

1.14 Circular Jet in Presence of a Boundary (i.e., a wing)

- 1.141 Solid boundary effect on inflow and noise
  - 1.1411 Flat surface parallel to jet axis
  - 1.1412 Cylindrical surface parallel to jet axis
  - 1.1413 Combined flat surface and cylindrical surface
  - 1.1414 Develop theory for effect of surfaces in proximity to jet

1.15 Noncircular Jets

- 1.151 Elliptical
- 1.152 Rectangular
- 1.153 Non-uniform cross-section shape

1.16 Effect of External Flow

1.161 Circular jet
1.162 Parallel jet
1.163 Coaxial jet

1.17 Effect of Lip on Noise Production

1.171 Circular jet

1.1711 Examine Kutta condition for sharp exit
1.1712 Blunt exit lip
1.1713 Effect of various slots at jet exit (Particularly for supersonic flows).

1.2 Effect of Internal Noise on Jet Noise

1.21 Effect of a quantifiable internal disturbance on jet noise

1.211 Sinusoidal
1.212 Impulsive (Measure transmission, refraction, effect on basic jet mixing).

1.22 Effect of Internal Turbulence on Jet Mixing

1.221 Vary magnitude and scale of turbulence

1.23 Struts and Bodies

1.231 Using wing unsteady properties, determine effect on jet mixing

1.2311 Determine effect of boundary-layer blowing or suction

1.232 Determine effect of streamlined contral bodies

1.2321 For various long and short bodies, determine effect of suction, blowing, and vortex generators

1.24 Effect of Combustion

1.241 On actual engine, measure the velocity and temperature fluctuation emanating from combustor
1.242 On actual engine, measure the velocity and temperature fluctuation as it progresses through the turbine
1.243 Investigate combustor design for elimination of major fluctuation causing noise

1.25 Turbine Unsteady Flow Effects

- 1.251 Determine, on actual engine, the noise emanating from turbine
- 1.252 Investigate propagation of disturbance throughout tail pipe to external jet and determine effect on jet exhaust noise
- 1.253 Develop simulation techniques for study in laboratory of turbine noise

1.3 Noise Reduction Techniques
(Based on the results of 1.1, 1.2, specific noise reduction techniques should be investigated).

1.31 Multitube

- 1.311 Number of tubes and geometrical spacing (shielding)

- 1.312 Cross sectional shape of tubes

1.32 Multitube Plus Ejector

- 1.321 Size and geometry of ejector - diameter-length
- 1.322 Effect of ejector acoustic lining
- 1.323 Aerodynamic design for performance at cruise

1.33 Additives

- 1.331 Large molecules
- 1.332 Ionization

1.34 Reflection and Refraction

- 1.341 Temperature gradients
- 1.342 Velocity gradient
- 1.343 Fluid injection having different speed of sound on outer boundary of jet

1.35 Shielding

- 1.351 Effect of wing on sound propagation
- 1.352 Effect of fuselage on sound propagation

2 - AIRFLOW-SURFACE INTERACTION

The aerodynamic noise created by a body moving through a fluid is important from several aspects. The STOL aircraft may gain its lift augmentation by the impingement of the jet exhaust against a flap system, or by flow over the upper surface of a wing/flap. The details of the flow dynamics become of utmost importance including such factors as unsteady transition from laminar to turbulent flow, shock-boundary layer interaction, vortices from wing tip or leading edge vortex of delta wings. Flow over wheels and struts and cavities such as the wheel well are all potential sources of noise. Recent experience of noise measurements from an aircraft flying with its engines off and with flaps and landing gear up, has indicated a considerable amount of noise. It is quite possible that flow induced noise may become important for landing aircraft if the noise of the propulsion system is reduced to as low as 80 EPNdB.

Most of the effort at the present time is directed at the STOL system, with many experiments being conducted for various lift augmentation systems. Typical noise results from model tests are shown on figure 12. The interaction noise spectra are shown for two cases, one having a plate parallel to the jet axis and the second having a simulated flap. There are two main points to be made--first the noise induced by the parallel plate is significantly increased over that of the jet alone for the very low frequencies only--the second point is that the simulated flap increased the noise throughout the frequency range from 10 to 18 dB. It was not anticipated that the parallel plate would have such an effect at low frequency. As a matter of fact, the study of flow induced noise is a relatively new subject and constitutes a primary research area.

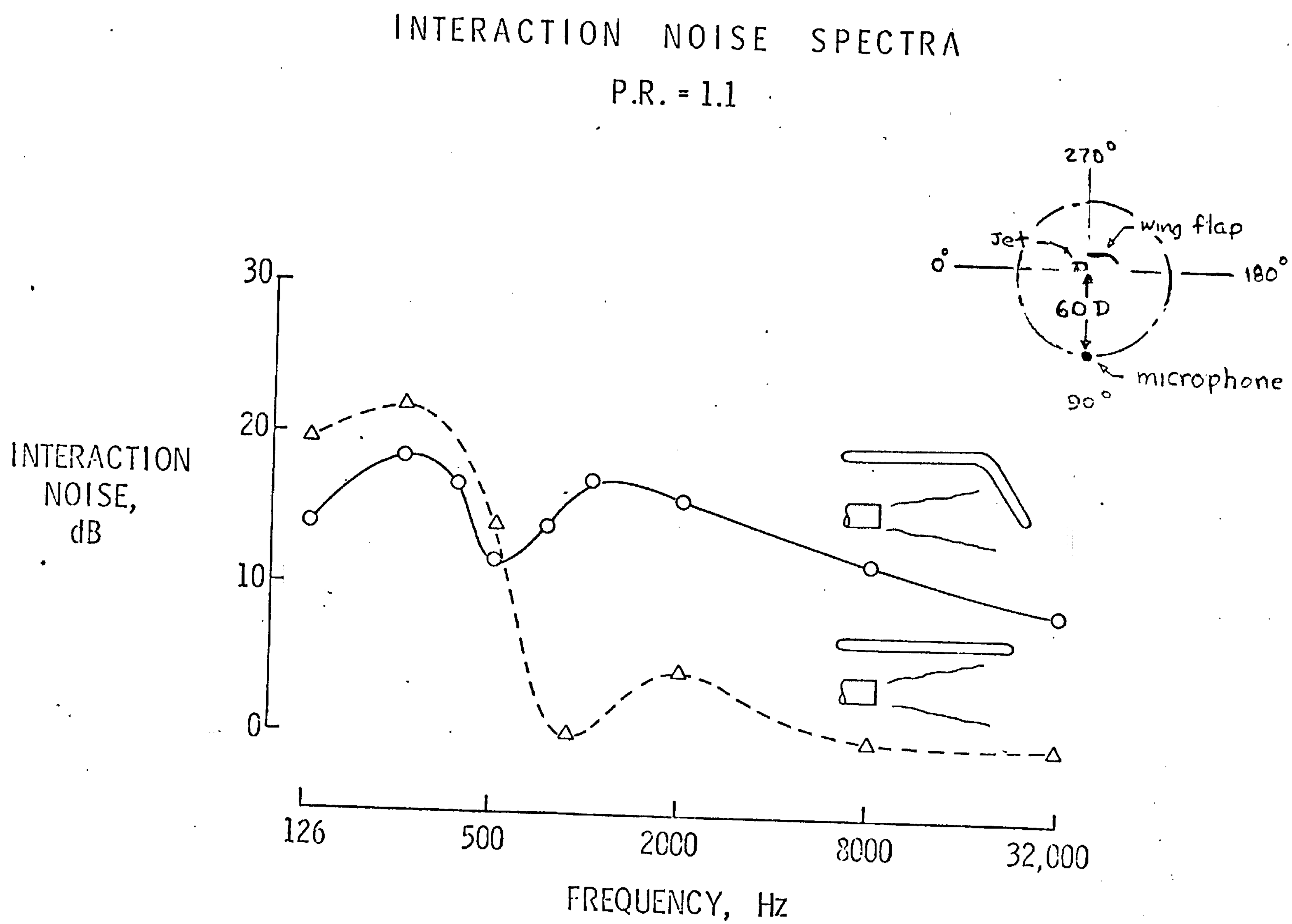


Fig. 12 INTERACTION NOISE SPECTRA

The work of Lighthill, discussed previously, is applicable to an unbounded medium at rest. Curle (ref. 9), in 1955, extended the work of Lighthill to include a bounded medium. The general solution of Lighthill's equation may be written as

$$\rho - \rho_0 = \frac{1}{4\pi a_0^2} \int_V \frac{\partial T_{ij}}{\partial y_i \, \partial y_j} \frac{d\,\tau(y)}{r}$$

where the integration is over the entire volume containing the quadrupoles. Curle showed that the solution to the general equation of aerodynamic sound for a bounded medium may be written as

$$\rho - \rho_0 = \frac{1}{4\pi a_0^2} \left\{ \frac{\partial^2}{\partial x_i \, \partial x_j} \int_V \frac{T_{ij}}{r} \, d\,\tau(y) - \frac{\partial}{\partial x_i} \int_S \frac{P_i - \rho v_i v_n}{r} \, d\tau(y) \right.$$

$$\left. - \int_S \frac{\partial}{\partial t} (\rho v_n) \frac{d\,\tau(y)}{r} \right\}$$

The first term T_{ij} represents the noise received at the field point directly from the quadrupole distribution in volume V. The term P_i represents the force exerted on the fluid at the surface S. The term $\rho v_i v_n$ is zero if the body is at rest since v_n represents the normal velocity of the surface, but otherwise is a measure of the momentum imparted to the fluid, and finally $\frac{\partial}{\partial t}(\rho v_n)$ represents a simple source and could be considered a thickness effect.

As for the unbounded medium, this equation is also difficult to solve and its application has been very limited, although these concepts have been used to investigate the radiation of sound from a turbulent boundary layer by Maestrello (ref. 20). An example of one attempt to use the Curle equation has been made by J. A. Drischler of Langley Research Center, in which he eliminated all terms except P_i, and based on some experimental results for the random pressures, and an assumption with regard to space correlation, he calculated the spectra of noise radiated from a rigid plate. The results of the calculations are shown in figure 13. This analysis will be correlated with experimental work; however, the experimental verification will require a large number of precision measurements of the fluctuating pressure over the area of the plate, which, in itself, is not an easy task.

To summarize the airflow-surface interaction, a relatively new field of research, the critical issues revolve around the experimental determination of various quantities required for Curle's equation and then the verification of the equation for prediction of the far field noise. A detailed program is given in the following outline.

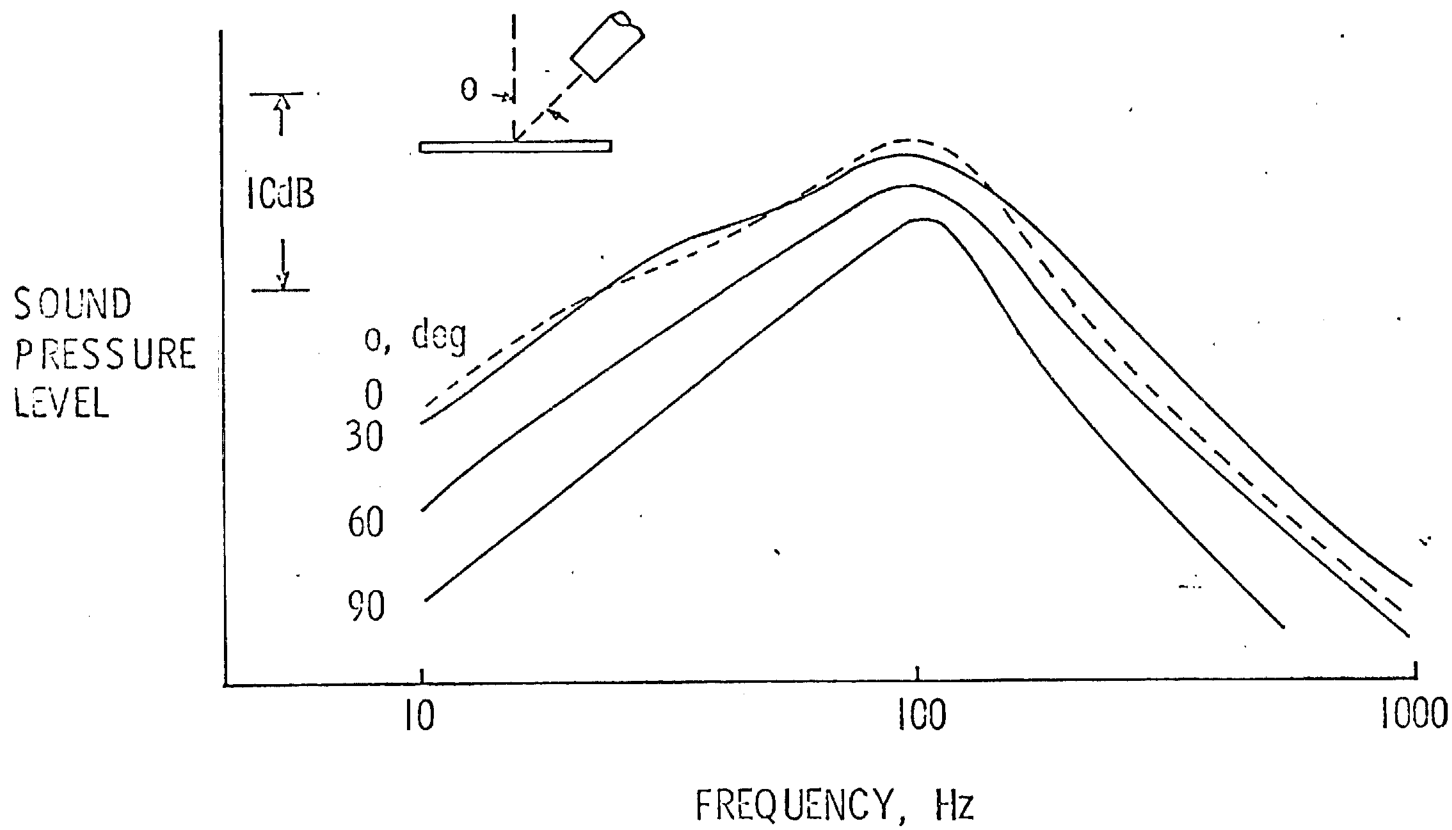


Fig. 13 CALCULATED EFFECT OF INCIDENCE ANGLE ON IMPINGEMENT NOISE

2 Airflow-Surface Interaction

2.0 Fundamental Airfoil Noise Sources

2.1 Stationary Airfoil - Two Dimensional

Measure - (1) Boundary-layer fluctuation on surface with imbedded pressure cells and externally with hot wires.

(2) Determine location of separated flow area and measure noise production.

(3) Measure trailing-edge fluctuation.

(4) Measure wake fluctuation and wake deficiency.

Analysis - Correlate pressure fluctuations with a field results.

Configurations - Investigate various forms of boundary-layer trips, possible suction or blowing - various trailing-edge configurations.

Cascade - Effects of cascading on boundary layer fluctuations.

2.11 Stationary Airfoil - Finite Aspect Ratio

2.111 Rectangular - (1) Measure noise from tip vortex.
(2) Blow jet into tip vortex core. Measure noise field, particularly for directional effects.

2.112 Delta - (1) Establish leading-edge vortex. Measure flow noise.

(2) At position of leading-edge vortex, simulate jet engine and measure noise field. (Are there directional effects?)

2.113 Tip configurations - (1) Measure noise for various tip shapes

(a) Square
(b) Rounded
(c) Triangular
(d) Pointed
(e) Ogee

2.2 Oscillating Airfoil

2.21 Two-dimensional - (1) Measurement of unsteady surface pressures and correlation with far field noise - check against theory.

(2) Investigation of dynamics of boundary layer on oscillating wing.

(3) Oscillating through stall - measurement of surface pressures and far field noise.

(4) Measurement of oscillating wake - correlation with far field and theory

2.22 Measure the oscillating wake velocity defect and correlate with theory.

2.23 Measure noise from oscillating wake impingement on another blade placed behind oscillating wing and correlate with theory.

2.30 Review and critical assessment of past work on jet impingement noise

2.31 Fundamental Study of Jet Impingement Noise

(For test, the measurements to be made should include the measurement of the unsteady flow on the surface of the impinged plate; the noise field, near and far; the external flow field including the flow entrainment, and the oscillation of the jet boundary. Correlate with Curle theory).

2.311 Jet Impingement on Infinite Plate

2.312 Jet Impingement on Finite Plate

Investigation of influence of trailing edge on noise amplification.

2.313 Jet Impingement on Wing/Flap Combination

2.314 Jet Flap

Jet efflux over top of wing and flap for various ratios of wing-flap Chord

2.315 Jet Blowing on Center Line of Wing Chord (Flow is separated between upper and lower surfaces)

2.316 Methods of Noise Reduction

2.3161 Boundary layer control
2.3162 Upper-lower surface bleeding

2.32 Impingement noise on blunt shapes
(Landing gear and wheel)

2.33 Noise due to cavities
(Wheel-well)

2.4 Complete Aircraft Flow Noise Measurement

2.41 Model test in wind tunnel
(Same configuration as full scale test in 2.42)

2.42 Flight Test of Operational Aircraft

3 - ROTATING BLADE NOISE

An integral part of the propulsion system of every aeronautical and nautical transporation system is the rotating blade-propellers, compressors, fans, helicopter blades, etc. The aerodynamics of a rotating blade, even in the steady case, is a most complex problem and resort is usually made to rather drastic simplifying assumptions. The unsteady case presents an even more formidable problem.

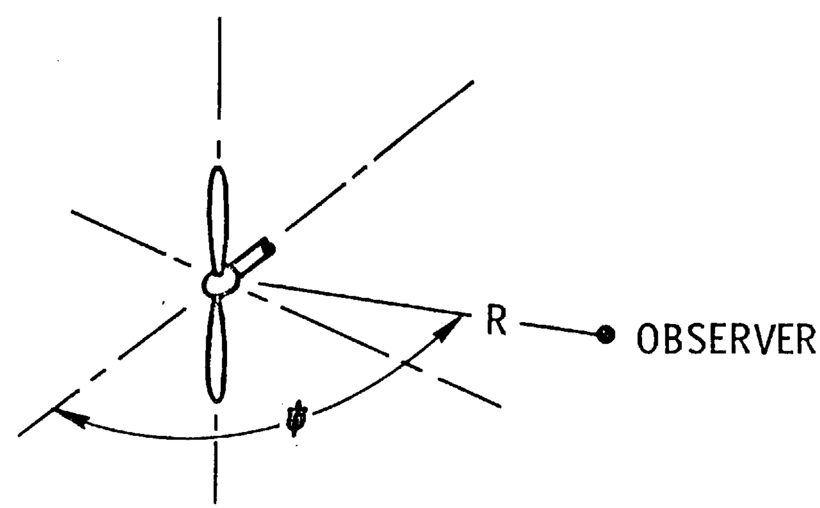
We shall divide the discussion into two parts, first, the rotating blade in a free-field exemplified by the propeller and helicopter blade. Secondly, we shall discuss the rotating blade in a duct, exemplified by the fan of a jet engine.

Free Rotor Noise Generation

The noise from a rotating blade arises from two sources, the first source results from the motion of a steady force relative to a fixed observer, that is, the rotor during one rotation moves relative to the observer and represents an apparent sound source, in spite of the fact that pressures on the rotor surface are steady. Gutin (ref. 21) derived the basic equation for this case which has been sufficiently accurate for the lower harmonics to be able to predict the pressures on adjacent surfaces such as the fuselage for sonic fatigue studies. Garrick and Watkins (ref. 22) later added the effects of forward speed to the Gutin theory. Recently both Lowson and Wright have shown that the higher harmonics are important and have explained the discrepancy which has existed between the Gutin theory results and experiment at the higher harmonics. Lowson (ref. 23) and Wright (ref. 24) have independently shown theoretically that the noise in the higher harmonic regime is due to unsteady load effects--which may result from a large number of causes. For instance, non-uniform inflow, blade vibration, unsteady flow on the blades due to flow breakdown, etc. The remainder of this section provides further details of the rotor source phenomena.

The basic equation for the classical Gutin theory of propeller and rotor noise is shown in figure 14. In this theory it is assumed that the blade load distribution does not vary with time. An element of area in the rotor disk receives an impulse each time a blade passes. These impulses are represented by a distribution of pressure dipoles over the disk, properly phased to take into account the time interval between successive blade passages. The amplitudes of the dipoles are obtained from the rotor thrust and torque distributions. The sound field produced by the pulsating dipoles is periodic and can be analyzed into a series of discrete harmonics. The fundamental frequency is $B\Omega$ where B is the number of blades and Ω is the rate of rotation. The amplitude of the n^{th} sound harmonic, $P_n(R,\psi)$, depends upon the rotor operating conditions and the observer positions (R,ψ) as shown in the equation. The Bessel function $J_{nB}\,(nBM_t \sin\psi)$ and the term $\cos\psi$ are responsible for certain characteristic directivity patterns which will be discussed later in the paper.

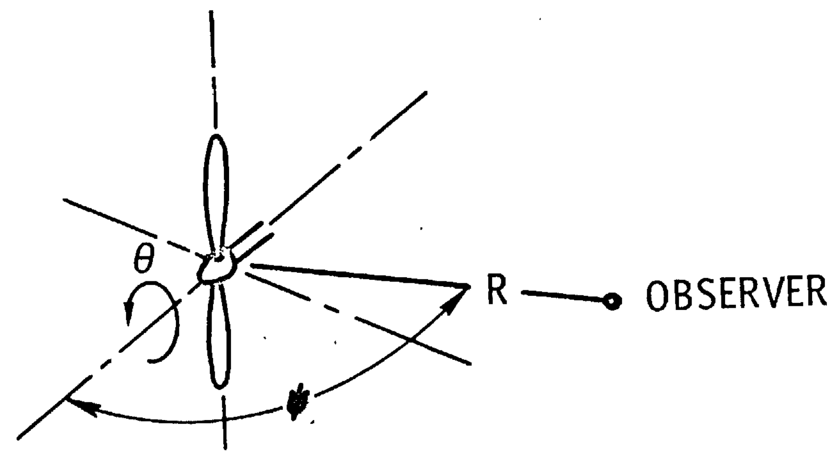
Noise radiation due to periodic variations of blade loading around the rotor disk was studied by S. Wright and M. Lowson. As indicated in figure 15, a periodic, but not necessarily sinusoidal, variation in thrust or torque around the rotor disk can be represented as



$$P_n(R,\psi) = \frac{nB\Omega}{2\pi cR}\left[T\cos\psi - \frac{Q}{M_t R_e}\right] J_{nB}(nBM_t \sin\psi)$$

n	HARMONIC NUMBER	T	THRUST
B	BLADE NUMBER	Q	TORQUE
Ω	SHAFT SPEED	R_e	EFFECTIVE RADIUS
M_t	TIP MACH NUMBER	J_{nB}	BESSEL FUNCTION

Fig. 14 NOISE RADIATION DUE TO STEADY BLADE LOADS



$$\begin{bmatrix} T \\ Q \end{bmatrix} = \sum_{\lambda=-\infty}^{+\infty} \begin{bmatrix} T_\lambda \\ Q_\lambda \end{bmatrix} e^{i\lambda\theta}$$

$$P_n(R,\theta,\psi) = \frac{1}{2\pi cR} \sum_{\lambda=-\infty}^{+\infty} \left\{ nB\Omega T_\lambda \cos\psi - \frac{\Omega Q_\lambda}{M_t R_e} (nB-\lambda) \right\} J_{nB-\lambda}(nBM_t \sin\psi) e^{-i\lambda\theta}$$

Fig. 15 NOISE RADIATION DUE TO PERIODIC BLADE LOADS a Fourier series of blade loading harmonics, T_λ in thrust and Q_λ in torque where λ is the loading harmonic number. Each of these loading harmonics contributes to the sound field which can be expressed as a series of harmonics with fundamental frequency $B\Omega$. The formula at the bottom of figure 15 is the expression for the amplitude of the n^{th} sound harmonic. The $\lambda = 0$ terms in this series correspond to the Gutin theory. It is seen that the amplitude of a single sound harmonic depends upon all of the loading harmonics and upon the observer's azimuth angle θ. Studies by Wright and Lowson indicate that the higher loading harmonics can be very efficient sound radiators which may completely overwhelm the noise due to the steady loads. This theory has received considerable attention in connection with helicopter noise radiation where it is applicable to such diverse phenomena as asymmetric loading due to forward flight, periodic vortex shedding, and impulsive loading due to blade slap.

The dependence of the loading harmonics, T_λ and Q_λ, on the operating conditions of a rotor is not well understood at the present time. From an analysis of limited experimental data, Lowson obtained an approximate trend for the amplitudes of T_λ and Q_λ which seemed to be valid for a wide range of operating conditions. However, this approximation is not universally accepted as the best compromise for all vehicles and flight regimes, and there are questions regarding the proper treatment of phase effects. Further experimental investigations involving simultaneous noise and blade loading measurements are clearly needed to resolve these questions.

The blade loads associated with several types of operating conditions are shown in figure 16. The solid curve represents an impulsive type of loading associated with blade slap. A nonimpulsive but still rapid change in loading such as might result from sudden loss of lift during blade stall is indicated by the dashed curve. Also shown are a still more gradual lift variation suggestive of forward flight and a steady blade load which is independent of time. All of these various types of loading could occur at different times if the vehicle is operated in an unsteady flight condition.

The blade loads shown here can be Fourier analyzed around the rotor disk to give the loading harmonic amplitudes T_λ and Q_λ. An impulsive load will have many harmonics of nearly equal amplitude, whereas, at the other extreme, a steady load has only one harmonic, the constant term in the Fourier series. The loading harmonics can then be used to compute the radiated noise from the equation at the bottom of figure 15. It appears from Lowson's and Wright's work that many loading harmonics may be necessary to accurately predict the higher sound harmonics.

Calculated trends of the amplitudes of the radiated sound harmonics for the various blade loads of figure 16 are shown in figure 17 (ref. 25). An impulsive loading gives rise to a sound spectrum which increases at 6 dB per octave. The blade stall type of loading gives a flat spectrum and the forward flight condition produces a spectrum which decreases at about 6 dB per octave. All three of the fluctuating loads are seen to predict sound harmonic amplitudes considerably higher than the steady load alone.

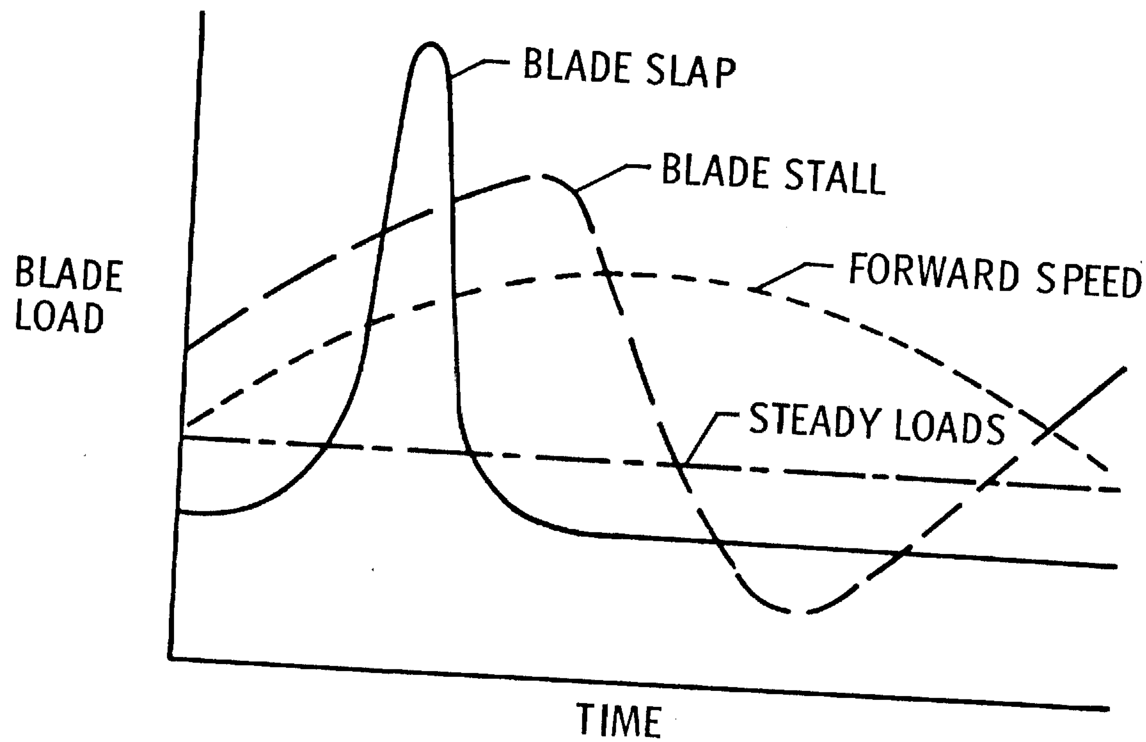


Fig. 16 SAMPLE FLUCTUATING LOAD TIME HISTORIES

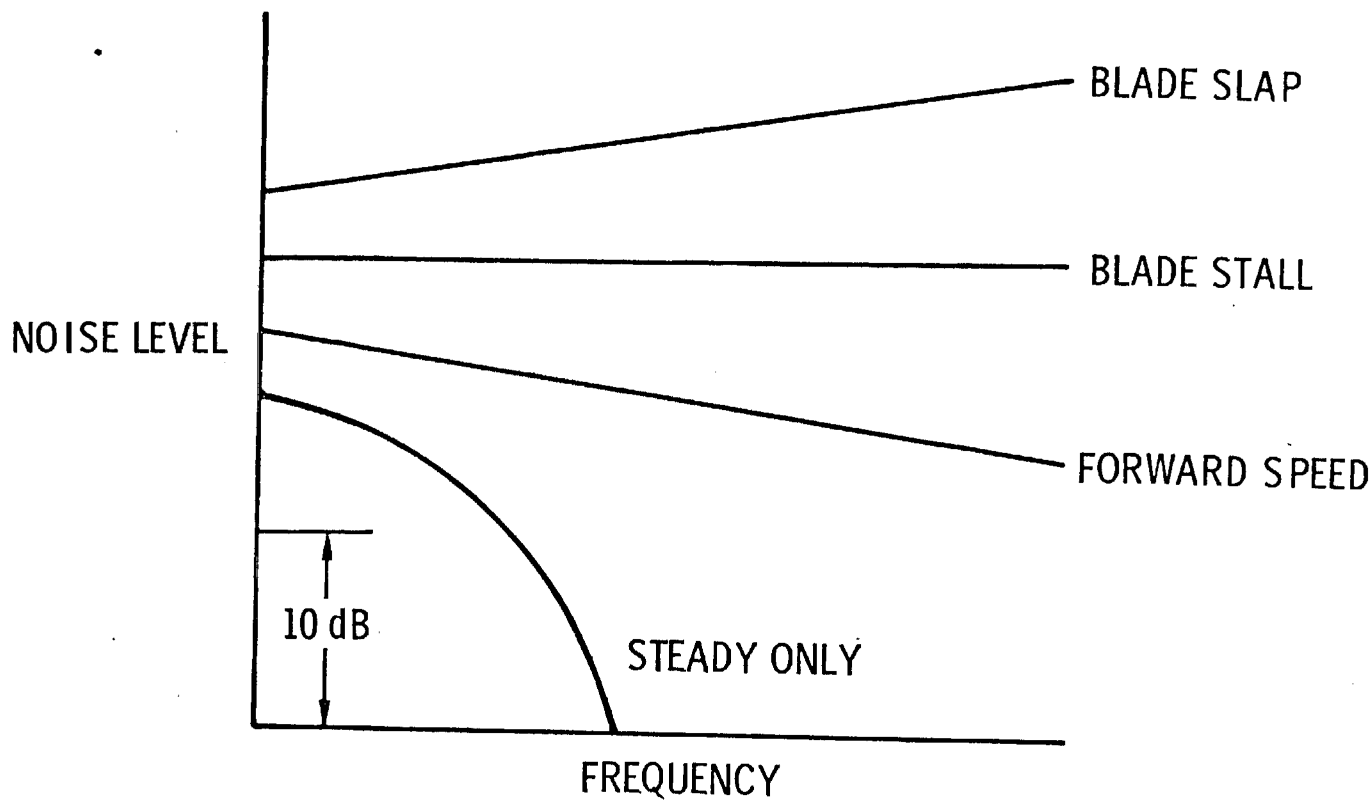


Fig. 17 ROTOR NOISE RADIATION FROM FLUCTUATING LOADS

Figure 18 contains schematic diagrams of the rotational noise radiation patterns from several rotor noise sources. (Note that amplitudes are not necessarily to scale.) For all of the radiation pattern sketches, the rotor orientation illustrated in the upper left applied; that is, the axis of rotation is vertical and the plane of rotation is horizontal. The noise due to steady torque is a maximum in the plane of rotation and a minimum on the axis. Likewise, the noise component due to thickness is a maximum in the plane of rotation. The noise component due to steady thrust has a four-leaf-clover pattern, as illustrated in the lower left sketch. The sketch at the lower right indicates the changes in directivity that occur in the thrust noise pattern due to unsteady thrust forces on a rotor in sideways motion. These latter results suggest that the directivity patterns become distorted in the direction of motion, and the maximum amplitude is larger than for the steady thrust case. The example shown represents a modest asymmetry of the thrust loads. In many actual cases of rotors in forward motion, the loading asymmetries can be more pronounced and the resulting noise pattern is more distorted.

An indication of the validity of the prediction methods of figures 16 and 17 is given in figure 19. Two sets of calculations of the noise levels for a helicopter in flight are compared with measured data. It can be seen that the calculated steady loads values are in best agreement at the lowest harmonic number but are markedly lower than the measurements at the higher harmonic numbers. On the other hand, the calculated unsteady loads values are in relatively good agreement with the measurements

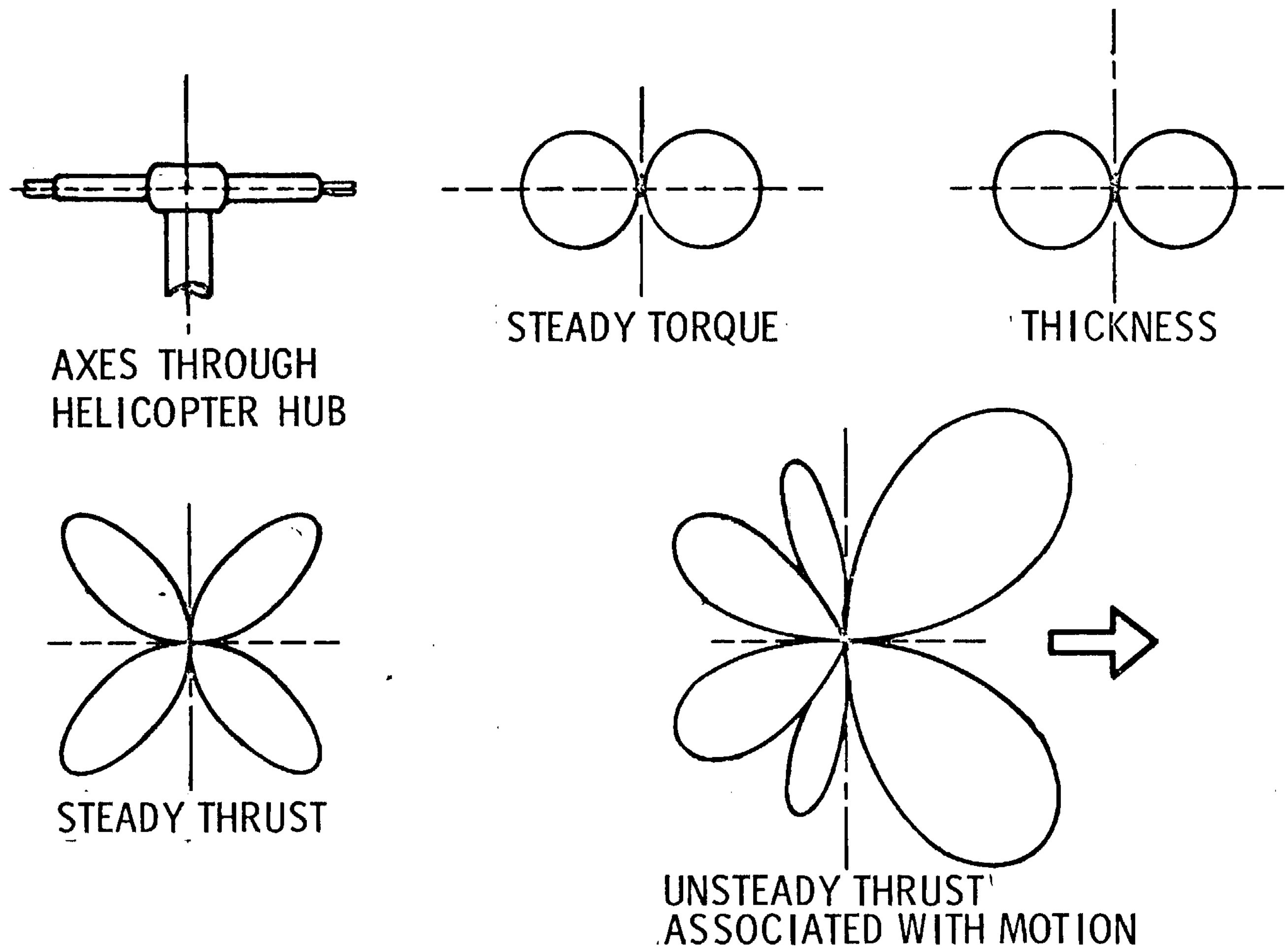


Fig. 18 ROTOR NOISE RADIATION PATTERNS

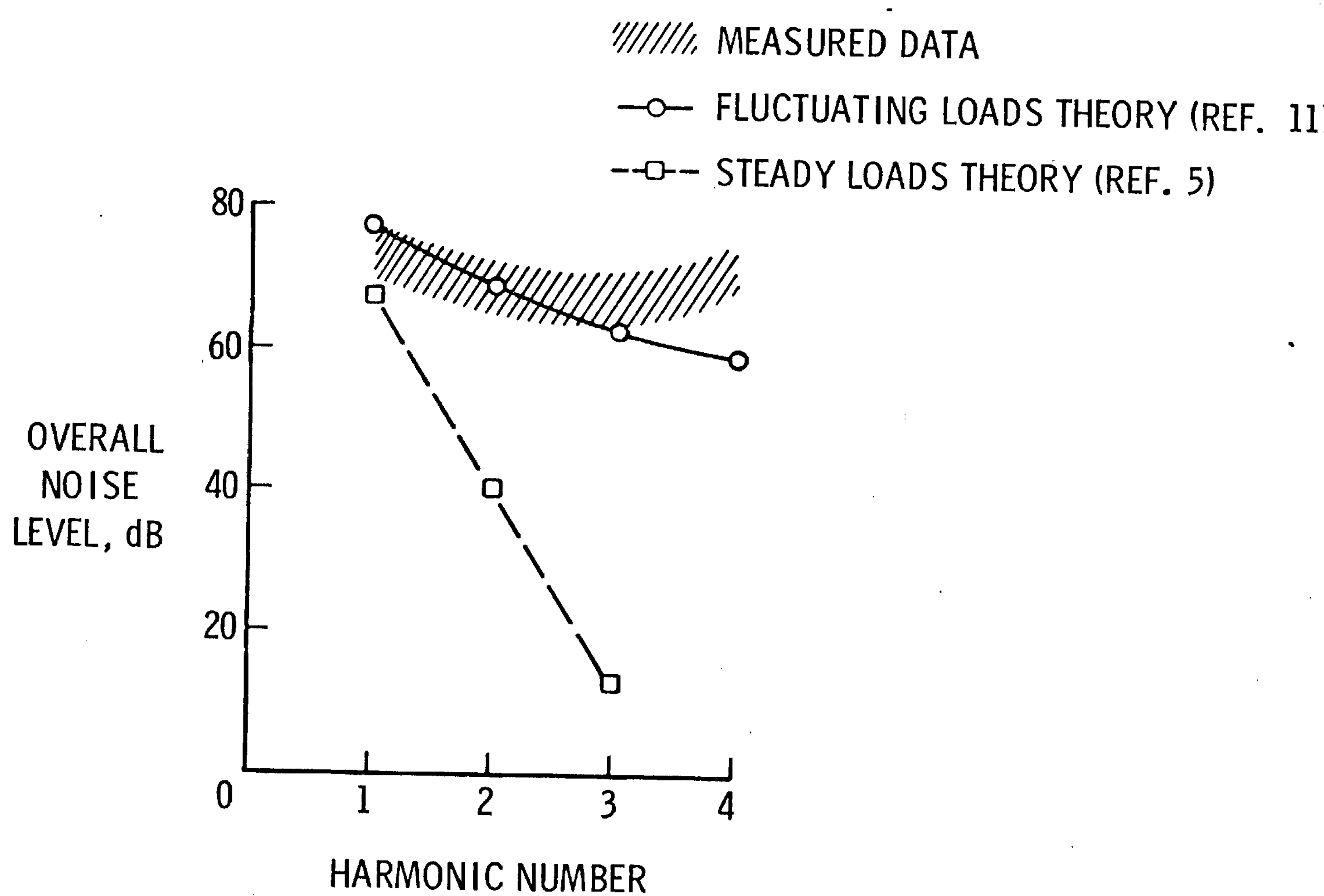


Fig. 19 HELICOPTER ROTOR ROTATIONAL NOISE

over the range of harmonic numbers. It may be concluded that the steady loads theory is useful for predicting low-order harmonic noises that are most significant for structural problems but is not adequate for predicting the higher order harmonic noises that are most significant for subjective reaction.

Broadband Noise Prediction

The theories discussed in the preceding section have been concerned with both steady and periodic blade loads and with the associated periodic noises. The viscosity of the medium can give rise to nonperiodic blade load fluctuations which are random in nature. These force fluctuations are the principal sources of broadband noise. There are a number of methods for predicting broadband noise levels for rotors based on a knowledge of gross geometric and operating parameters. Predictions starting from a knowledge of the underlying physical phenomena will require use of methods from random process theory. Broadband noise from compressors, helicopters, and propellers involve random fluctuating force distributions on several rotating blades. The extension to account for rotation has been carried out by Ffowcs-Williams. Blade-to-blade correlation and modulation effects of rotation may then also become important. Application of these concepts to practical cases requires auto-correlation information which is difficult to measure.

Broadband noise from a free rotor is known to be a function of the geometry and operating conditions of the rotor. In order to illustrate the effects of some of the significant factors in rotor noise, the data of figure 20 is included. These data were obtained from two-bladed

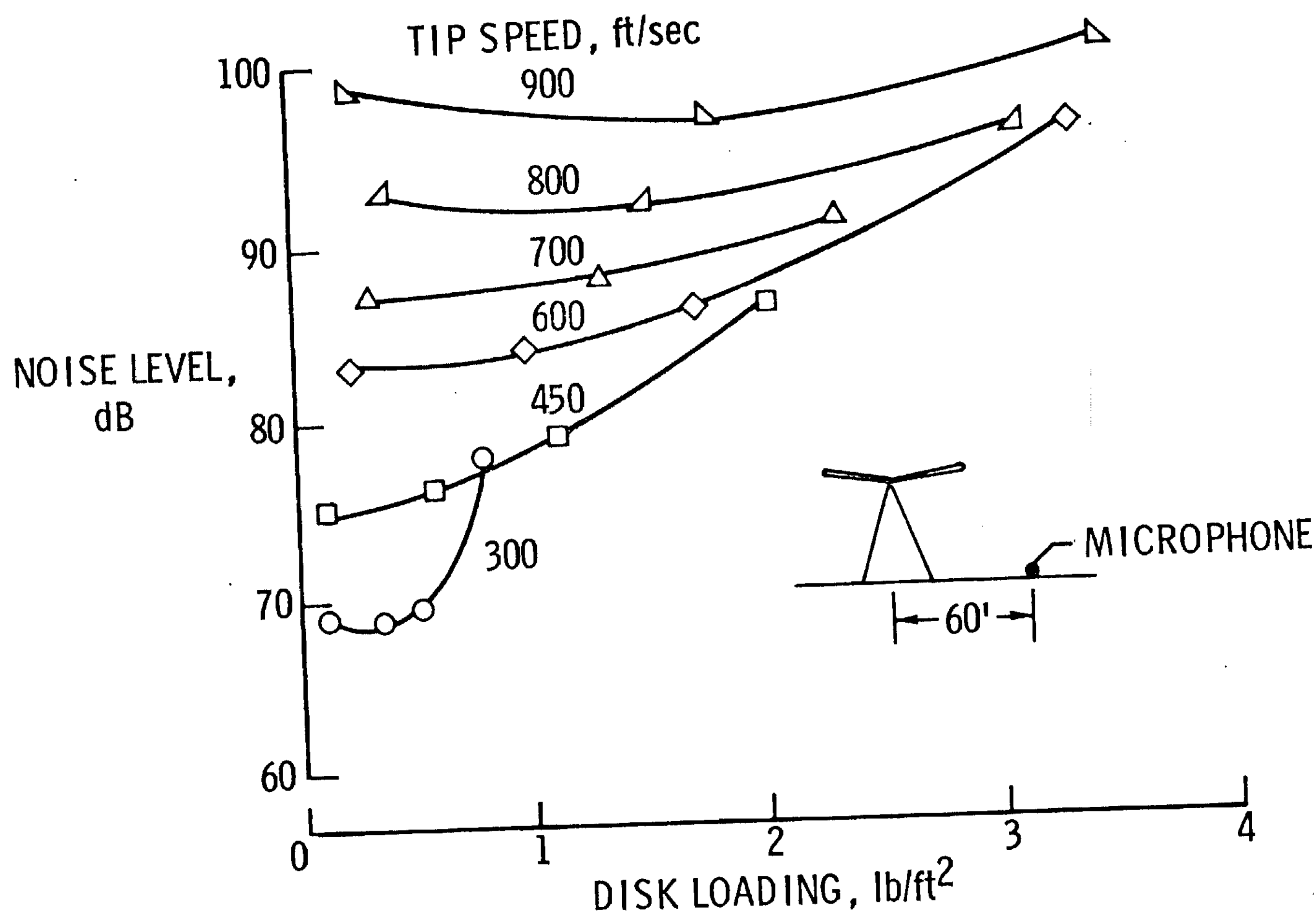


Fig. 20 TIP SPEED AND DISK LOADING EFFECTS ON ROTOR NOISE

helicopter rotors operating on a helicopter rotor test tower at various tip speeds and disk loadings. Noise measurements were made at stations on the ground at distances varying from 60 to 100 ft. from the center of rotation. The noise data contain both discrete frequency and broadband components; however, the broadband components either dominate or are significant for all the cases presented.

The data of figure 20 are for a 52-ft-diam two-blade rotor at a measuring point 60 ft from the axis of rotation at ground level. It can be seen that both tip speed and disk loading affect the overall noise levels. For instance, at a given value of disk loading the noise levels decrease markedly as tip speed decreases, particularly at the lower disk loadings. Likewise, at any particular tip speed, the noise levels decrease as the disk loading decreases.

The state-of-the-art is, in summary form, that we can predict the lower harmonic of the periodic noise of a propeller or rotor, but the older theory breaks down for the higher harmonics which are important for subjective ratings. If the unsteady pressures on a blade are known, methods are available for predicting the broadband noise. Research, therefore, must be directed at studying the details of the unsteady flow on rotor blades, particularly near the tip region. A detailed program is given in the following outline.

3 Rotating Blades

3.1 Fundamental Investigation of Unsteady Blade Loads Free Field

3.11 Measure the unsteady pressure distribution on same blade shape and planform as used in 2.11 and 2.21 (no forward velocity).

3.111 Model test in wind tunnel
3.112 Static full scale
3.113 In-flight full scale
3.114 Correlate with theory and far field noise

3.2 Unsteady Pressure Distribution in Forward Flight

3.21 Model test in wind tunnel
3.22 In-flight full scale
3.23 Correlation of model and flight

3.3 Boundary-Layer Studies

3.31 Develop instrumentation for measurement of unsteady boundary layer and transition region on rotating blade.

3.32 Utilize instrumentation on blades developed for 3.11

3.34 Measure Flow Field in Static and Forward Velocity

3.41 Correlate flow field measurement with the model and full scale.

3.42 Determine position of tip vortex with different tip planform. Develop theory.

3.43 Measure noise from tip vortex interaction with following blade. Correlate with theory.

3.44 Place a tail rotor in flow field from main rotor. Measure noise and correlate with theory.

3.45 Place a lifting surface in close proximity to tail rotor and determine noise field.

3.1 Rotating Blade Ducted

3.11 Measure steady flow on rotating blade and duct wall. (Use same blades as used in free field tests). Subsonic, transonic, and supersonic tip speeds. Measure wake.

3.12 Repeat 3.11, with stators installed in front of and behind rotor with various spacings.

3.121 Determine wake flow field and stator pressures.
3.122 Determine noise from stators.

3.13 Repeat 3.11 and 3.12 for

3.131 Non-uniform inflow.
3.132 Inflow turbulence.

3.14 Investigate vibration characteristic of blades.

3.141 Determine noise generation due to vibration of blades, and evaluate importance.

4 - SONIC BOOM

An aircraft flying at supersonic speeds creates a system of shock waves which at times may extend to as much as 50 miles from the aircraft. The public concern for exposure to this impulsive load has had two immediate effects, (1) the restriction of commercial operation to over water flights and (2) suspension of the development of a U.S. supersonic transport airplane.

An extensive amount of work has been done in the last several years in studying the sonic boom, its generation, propagation, and effect on people and structures. A listing of flight research is given in tables I and II. Over 2000 flights have been made resulting in 15,000 measurements. In spite of this intensive research, no method has been found to eliminate the sonic boom, although various ideas have been put forth which would provide for a lower sonic boom.

Therefore, the two critical issues facing the researcher are (1) to develop an aircraft having a very low boom and (2) to establish the maximum boom that will be acceptable to the community.

The remaining portion of this section will be devoted to (1) a general discussion of the elements of sonic boom, (2) historical review of the more important works, (3) attempts at minimization, (4) human factors and related aspects.

Elements of Sonic Boom Problems - At aircraft speeds below the speed of sound, disturbances travel ahead of the airplane and an observer on the ground hears the airplane before it actually reaches the vicinity of the observer. For supersonic speeds, on the other hand, the aircraft

TABLE I.- CHRONOLOGY OF U. S. SONIC BOOM FLIGHT RESEARCH

LOCATION OF STUDY	PARTICIPATING AGENCIES	CALENDAR YEARS 50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71
WPAFB	USAF																						
WPAFB-EDWARDS	USAF																						
WPAFB-EDWARDS	USAF																						
EDWARDS AFB	NASA																						
EGLIN AFB	USAF/USA																						
WALLOPS STATION	NASA																						
WALLOPS STATION	NASA																						
WPAFB	USAF																						
NELLIS AFB	NASA/USAF																						
EDWARDS AFB	NASA/USAF/FAA																						
ST. LOUIS	NASA/USAF/FAA																						
X COUNTRY SPEED RUN B-58	USAF																						
WALLOPS STATION	NASA/USAF/USN/FAA																						
EDWARDS AFB	NASA/USAF/USN/FAA																						
OKLAHOMA CITY	NASA/USAF/FAA																						
WHITE SANDS	USAF/FAA																						
EDWARDS AFB	NASA																						
CHICAGO	NASA/USAF																						
WALLOPS STATION	NASA/USAF/USN																						
JTF-2 (TONAPAH)	USAF																						
EDWARDS AFB (B-70)	NASA/USAF																						
PENDLETON, OR	FAA/ESSA																						
JACKASS FLATS, NV	NASA/DOT/USAF/AEC																						
APOLLO 15	NASA																						

GENERATION AND PROPAGATION

STRUCTURAL INTERACTION

PSYCHOACOUSTIC

ATMOSPHERIC INTERACTION

TABLE II.- SONIC BOOM FLIGHT TEST VARIABLES

VARIABLE	RANGE OF VALUES
AIRPLANE TYPE	F-100, F-101, F-104, F-105, F-106, F-111, F-4, F-8U1, F-8U3, T-38, B-58, SR-71, XB-70, X-15
WEIGHT, lb	10,000 - 500,000
SIZE, ft	45 - 185
ALTITUDE, ft	50 - 90,000 +
MACH NUMBER	0.98 - 3.0 +
Δp, lb/ft^2	0 - 120
NUMBER FLIGHTS	OVER 2000
NUMBER MEASUREMENTS	OVER 15,000

outruns the disturbances which eventually pile up in a wave having a sharp pressure discontinuity. These pressure discontinuities create the boom that we hear when a supersonic airplane passes the observer. On figure 21 we have sketched a shockwave pattern from a supersonic airplane as it progresses from the airplane to the ground. Close to the airplane there is a very complex pattern of shock waves arising from changes in the aircraft geometry such as the intersection of the wing with the fuselage, the cockpit, the tail, the engines, etc. Each one of these discontinuities creates a shock wave. However, the leading shock wave increases the speed of sound by an infinitesimal amount. The next shock wave operating in this higher speed of sound environment will advance at a faster rate than the original shock wave and this occurs in succession as one progresses away from the airplane nose through the various shock waves. This then has a tendency to cause the shock waves to pile up so that eventually at a very long distance from the airplane, measured in miles, the detailed form that we saw near the aircraft develops into a front shock wave. For the rear portion of the shock pattern, an expansion occurs so that the speed of sound is lowered, and the rear shock waves will also coalesce into a single closure shock. Thus the classical N-wave is formed a large distance from the aircraft. (Hayes has remarked that it is possible for a shock wave pattern to become "frozen" before the establishment of an N-wave which depends on the atmospheric scale height.) Some of the major factors that influence this pressure discontinuity, the sonic boom, are airplane weight--the greater the airplane weight, the larger the pressure discontinuity, and thus, the greater the sonic boom pressure. Altitude has a

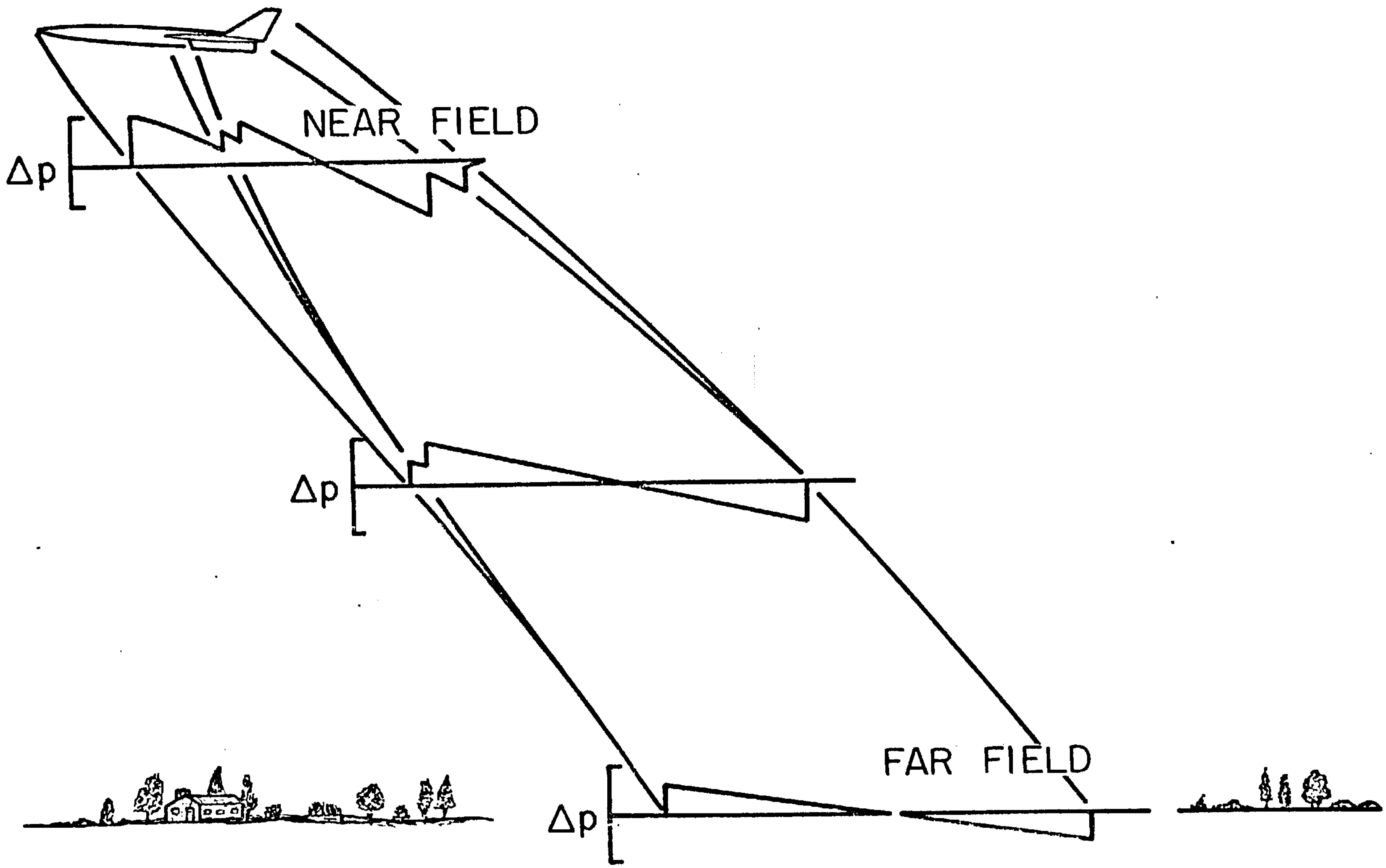


Fig. 21 AIRPLANE PRESSURE FIELD

beneficial effect in that it tends to reduce the sonic boom pressure. The sonic boom will increase with airplane size, in particular, the cross sectional area. Mach number has a slightly beneficial effect as one leaves the transonic region and progresses to higher Mach numbers. The effect of temperature distribution in the atmosphere will change the speed of sound, which will change the orientation of the various shock waves and their strength and can have a rather large effect on the imposed pressures on the ground. Acceleration and maneuver can cause very high pressure shocks well above those of the level, constant speed flight. Atmospheric turbulence can change a shock wave from a normal N-wave to a very peaked wave or can even reduce it to a rather low level without the step. The effect of buildings can cause multiple reflections of the shock waves, increasing the boom pressures in one area and reducing it in another. Thus, there are many factors that influence the sonic boom.

<u>Historical Review</u> - Hayes presented in a Ph.D. thesis (ref. 26) a basic theory for sonic boom development and propagation. Unfortunately, it was hidden in this rather obscure document and the knowledge of this work was not apparent to the workers who suddenly became concerned with the sonic boom. The paper that has formed the basis for most of the work on sonic boom was by Whitham (ref. 27) entitled "The Flow Pattern of a Supersonic Projectile." The theory developed by Whitham was essentially a linearized theory with an adjustment for a quasi non-linear approach in handling the shock wave. The Whitham approach will not predict the proper shock wave profile close to the airplane. It is essentially a far field analysis; however,

it has been shown many times to give a very adequate definition of the shock wave shape a long distance from the airfoil. The next major theoretical development was a paper by Walkden (ref. 28) in which he added the effect of lift to the Whitham theory, since that theory was concerned only with a non-lifting body. With this as a background, then Carlson and Maglieri (ref. 29) mechanized the theory, including the so called "F" function which charaterizes the shape of the airplane, into a working program. The effect of the atmosphere was treated by Randall (ref. 30) and finally definitized in a computer program by Friedman (ref. 31). The final development, essentially a complete sonic boom theory for propagation through a non-uniform atmosphere, was made by Hayes (ref. 32).

An illustration of the correlation of theory and flight tests is shown on figure 22, where overpressure is plotted against altitude. In general, good correlation is obtained between theory and experiment for these cases of level, non-accelerating flights. For maneuvers and accelerations, theory will predict the location of the focused boom but will not predict the magnitude of the boom. Thus, one of the critical issues in the further development of the theory is to develop a non-linear theory which will provide for a quantitative definition of the overpressure.

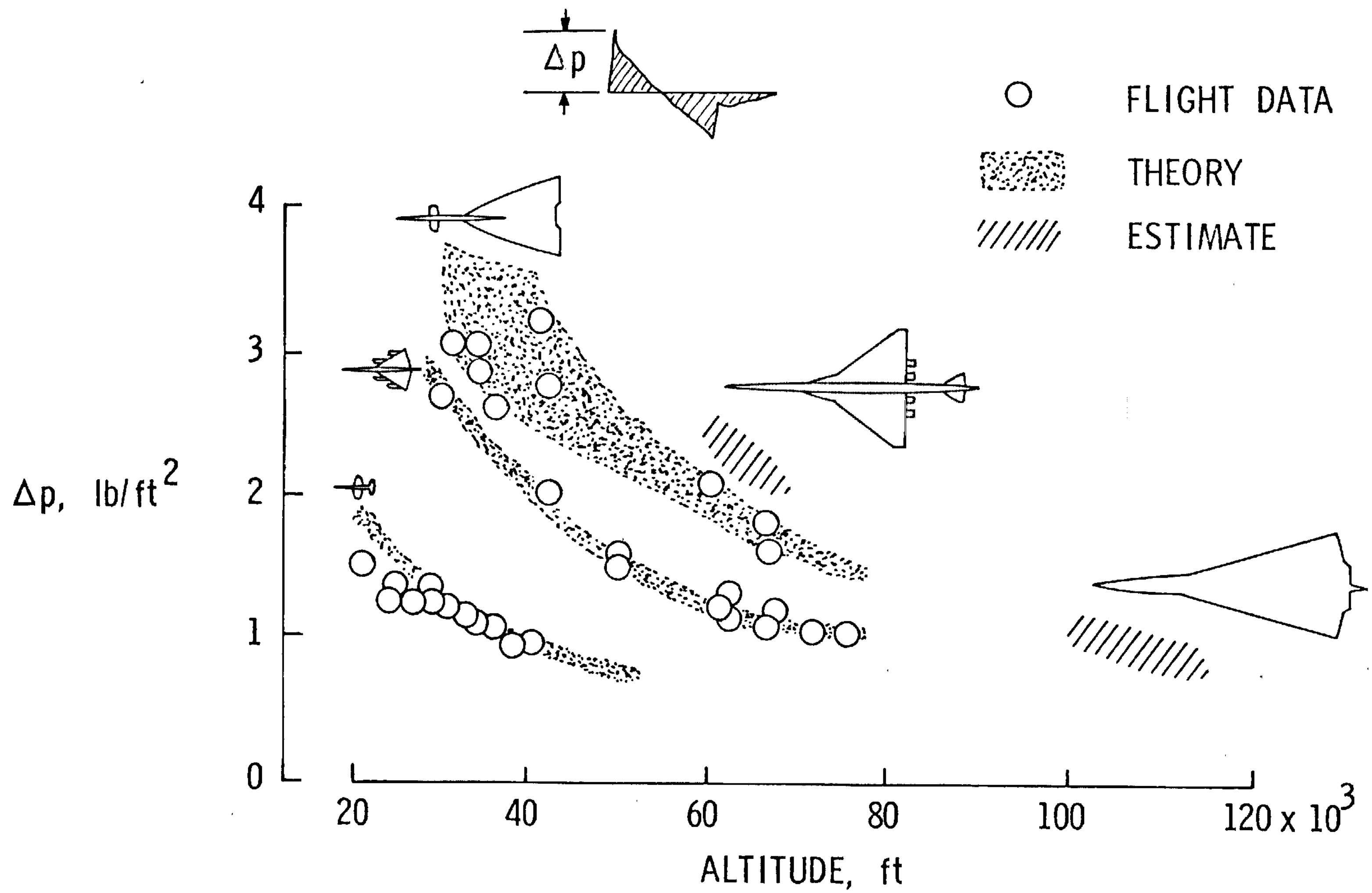


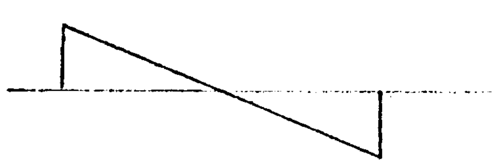
Fig. 22 SONIC BOOM OVERPRESSURES

<u>Sonic Boom Minimization</u> - Considerable attention has been directed at developing a zero or minimum boom airplane, and for the most part, these efforts have proved unsuccessful. Of course, the aircraft designer is still dependent on the human factors researcher to determine the maximum boom that the community will accept.

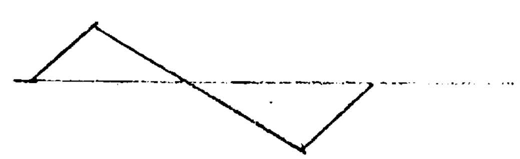
It should be recognized that lift produced by an aircraft must be counterbalanced by an increase in pressure on the ground equivalent to the airplane weight. For subsonic flight, the increase in pressure is distributed over a very large area, and is consequently a very low pressure, so that subjectively, it is not possible for a human to detect the pressure rise. For a supersonic airplane, however, the increase in pressure is contained in a very limited area, between the front and rear shock locations, hence the pressure rise is very rapid and can be heard by the community. Actually, Busemann, ref. 33, in 1935 described the "Busemann Biplane," which did not produce a boom extending to the ground, but unfortunately, the configuration did not carry lift. When lift is obtained on the configuration, a boom then is created. A recent discussion of sonic-boom minimization was given by Seebass, ref. 34 .

In many attempts at sonic boom minimization, recognition of the importance of the rise time from the standpoint of human response was made. The concept is illustrated below where the normal N-wave boom is shown on the left and a boom with finite rise time is shown on the right.

N-wave



Finite rise time



Subjectively, the finite rise time boom should be less objectionable since the startle effect would be lessened, and the shape approaches that of a very low frequency sine wave. However, the boom shape may be worse from the standpoint of building response, since it may excite the lower vibration modes of the dwelling and cause a rattling of loose objects.

Some of the attempts at minimization may be categorized as shown below:

(1) Airplane Geometry

(a) Near Field Effect - McLean (ref. 35) proposed to utilize the near field shock waves since the number of shocks have not yet coalesced to form the front and rear shocks and hence the pressure rise would be less.

(b) Lift Distribution - Ferri (ref. 36) has shown that by distributing the lift in a more optimal manner, the overpressure may be reduced to less than 1 psf.

(c) The "sine wave" boom may be obtained from a very long aircraft with proper geometry. The aircraft may be of the order of 1,000 ft. to obtain the proper sine wave type boom.

(2) Phantom Shapes

(a) Heat or Force Field - Numerous attempts have been made to create a phantom body by the addition of heat or by ionization along with electromagnetic field to create the effect of a very long body. This would result again in the "sine wave" type boom as discussed previously. Miller and Carlson (ref. 37) have investigated the power requirements and have deduced that a power expenditure roughly equivalent to twice that necessary to sustain the airplane in steady level flight would be necessary. The means of delivering this heat or ionization is not clear and would require a considerable amount of research. Batdorf (ref. 38) has proposed an off axis heat addition by means of a thermal keel, suspended below the airplane. This system is under test to evaluate its potential.

In summary, it is apparent that sonic boom minimization will require a substantial amount of research before a practical system is found, in the meantime--the supersonic transport will probably be restricted to over water flight for a number of years.

Human Response Aspects of Sonic Boom - As mentioned previously, the key to the development of a second generation SST which would be acceptable for over land flight is the specification of the acceptable sonic boom exposure. In spite of a relatively large amount of work that has taken place in the past, we are still not in a technical position to define a criterion, although from the accumulated evidence, it appears that the overpressure level must be less than 1 psf--but how much below this level is the real question. Other factors, of course, must be investigated such as the influence of the shape of the boom signature, the number of boom exposures per day, the difference between daytime and nighttime.

Tests on human subjects have been made in the U.S. as well as England and France. A table of these various tests is given below. No attempt will be made here to review all of these activities. A few results will be singled out for discussion.

TABLE III Summary of laboratory, field, and community studies of human exposures to sonic boom

Laboratory studies	Field and community studies
Annoyance and loudness	A/C noise versus sonic boom
* Shepherd and Sutherland	Webb and Warren
Zepler and Harel	*Kryter
A/C noise versus sonic boom	Whole body response
* Pearson and Kryter	*Maglieri et al.
Broadbent and Robinson	White Sands
Startle (EMG)	Nixon et al.
* Lucas and Kryter	Community response
TTS/impulse	St. Louis
Rice and Coles	Oklahoma City
Nixon	Edwards
Performance	SR-71
* Lucas, Peeler, and Kryter	Crackerjack
Woodhead	Westminster
Harris	France
Sleep	
* Lucas and Kryter	

*Those studies with an asterisk were sponsored by the Langley Research Center

Based on the large background of experience with annoyance due to the random noise criteria developed for subsonic aircraft in subjective testing, Pearson and Kryter utilized a boom intensity of 1.7 psf and found the equivalent subsonic aircraft noise to be 113 PNdB indoors and 94 PNdB outdoors. If this relationship were valid, then one could calculate the composite noise rating (CNR)

$$\text{CNR} = \text{average peak PNdB} - 12 + 10 \log_{10} N \qquad N > 1$$

where N is the number of daily occurrences. A CNR rating of 100-110 is considered acceptable around airports at the present time.

Numerous programmed flight tests over large populated areas have been made; the most comprehensive was perhaps the sonic boom tests made over Oklahoma City (ref. 39). During these tests, the city was exposed to eight booms per day at a level of about 1.2 psf for a six month period. An interesting plot of the total number of calls to the complaint center against time is shown in figure 23. The telephone calls reached almost 1750 per day, and then rapidly fell to about 250 calls, which showed some adaptability to the booms.

Another series of sonic boom tests were conducted at Edwards Air Force Base, California with several types of aircraft, ref. 40, and the results are plotted in figure 24. The percentage of people

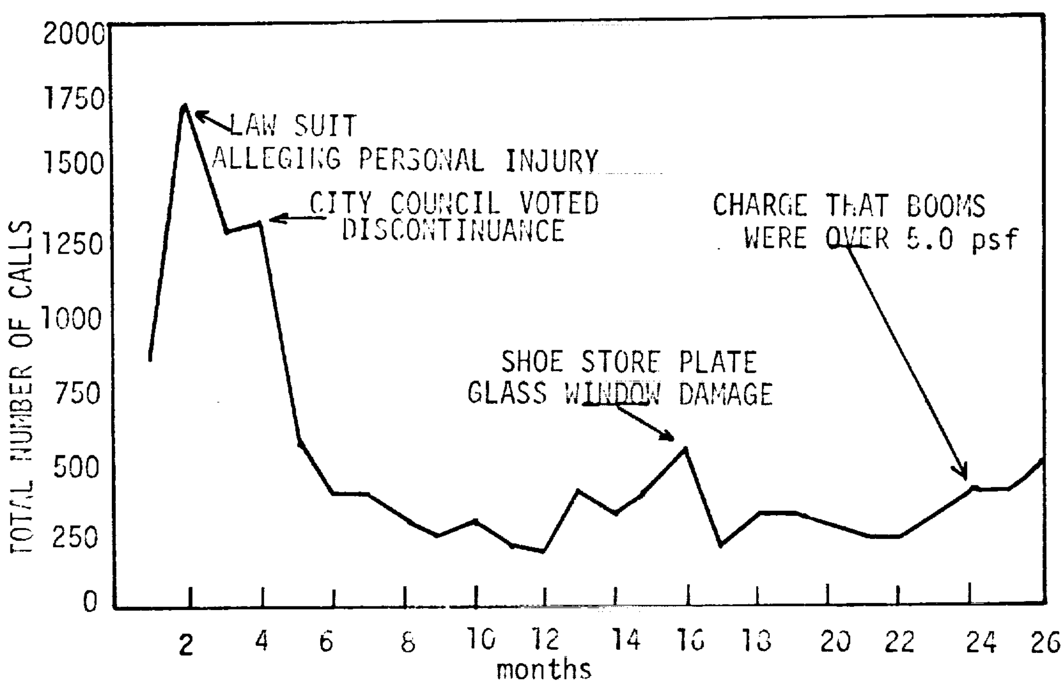


Fig. 23 CHRONOLOGY OF COMPLAINTS IN OKLAHOMA CITY STUDY

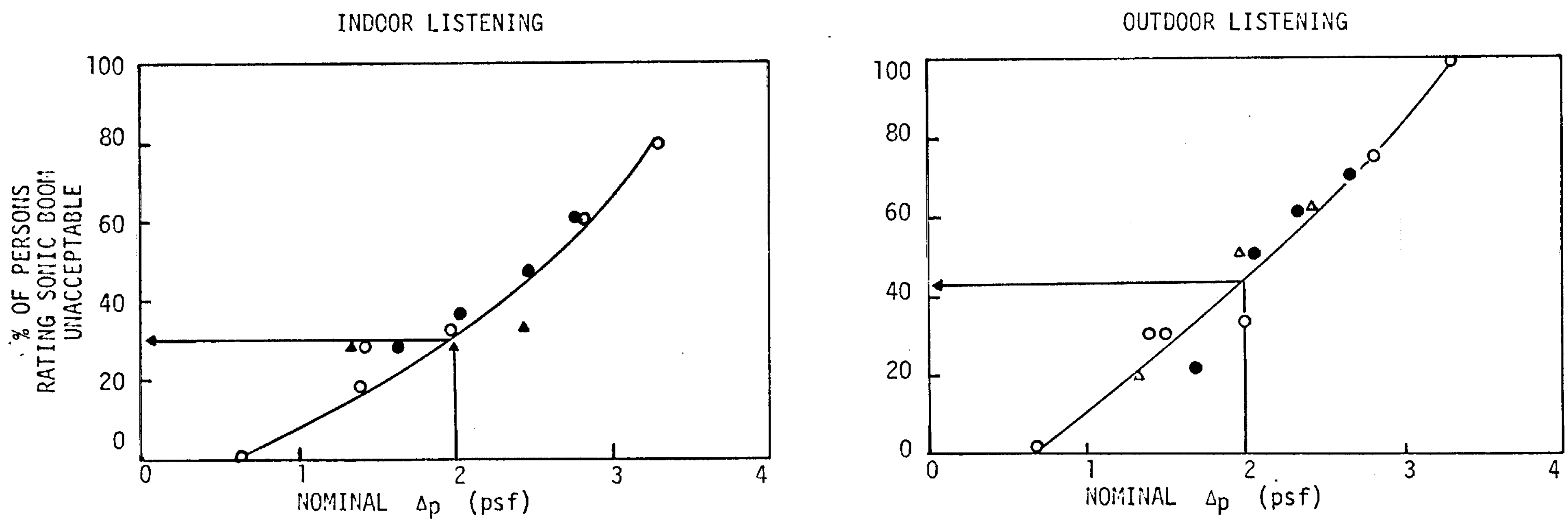

INDOOR LISTENING
OUTDOOR LISTENING
% OF PERSONS RATING SONIC BOOM UNACCEPTABLE
100
80
60
40
20
0
0
1
2
3
4
NOMINAL Δp (psf)

Fig. 24

rating the boom as unacceptable is plotted against nominal overpressure. Of great significance is the fact that the very few people considered the boom unacceptable when the boom overpressure was less than 1 psf--of the order of .6 to .75 psf. These data are felt to be very significant and research on the subjective effects of boom for Δ p's less than 1 psf should be done. Most of the sonic boom subjective work has been accomplished in the range of Δ p's from 1.2 to 2.6 psf and it is felt that an SST having booms in these ranges will not be acceptable for overland use.

Summary and Recommendations - Based on the laboratory and over-flight studies, the following observations can be made:

(1) The sonic boom levels associated with nominal SST operation are not in the range to create auditory damage.

(2) Some adjustment to sonic boom is realized after exposure for several months in a large community.

(3) Boom levels less than 1 psf will be required for overland flight. Research is required to definitize the maximum level acceptable.

(4) Experience with aircraft engine noise subjective ratings may provide a means for evaluating the sonic boom annoyance but more research is needed. CNR may prove to be an acceptable rating.

(5) Research should be directed at developing a very low boom airplane, which would be within the acceptable limits set by additional research on the boom levels and shapes found to be within human tolerance.

A detailed program is given in the following outline.

4 Sonic Boom

4.0 Establish Acceptable Levels of Overpressure

- 4.01 Human Response
  - 4.101 Effect of overpressure shape (rise time, flat-top, etc.)
- 4.02 Building Response
  - 4.101 Effect of Overpressure shape
- 4.03 Ground Motion

4.1 Sonic Boom Minimization

- 4.11 Lift and Drag optimization for minimum boom
- 4.12 Phantom Body
  - 4.121 Heat addition
  - 4.122 Ionization

4.2 Extend Theory to Include

- 4.21 Hypersonic velocities
- 4.22 Focus pressures
- 4.23 Effect of atmospheric variability

Influences of the Duct in the Rotor Noise Problem

If a rotor operates within a duct, additional phenomena are significant and must be taken into account. These phenomena result from the fact that the sound field is confined laterally. Under these conditions, the wave equation has solutions in the form of a discrete spectrum of eigenfunctions or modes. These modes are standing wave patterns of pressure across the duct which, once excited, propagate along the duct without change of form, but possibly with change in amplitude due to attenuation. The importance of the mode concept arises from the fact that the acoustic field generated in the duct by any source distribution can be represented as a linear combination of the modes. Hence, anything which influences the shapes of the modes or their attenuation also influences the transmission of sound along the duct and ultimately the sound radiated out through an inlet or exhaust.

The primary factors which affect the shapes and attenuation of the modes in a duct due to a sound source in the duct are: acoustic impedance of the walls, sound frequency, airflow in the duct, and cross-sectional area development. The principal effect of wall impedance is to increase the axial attenuation of the modes and hence to reduce sound transmission and radiation. In the presence of absorptive walls, the mode shapes are dependent upon the sound frequency. Cross-sectional area development affects the cutoff frequencies in the duct as well as mode shapes. An increasing cross-sectional area will enhance radiation by improving the impedance match between the interior and exterior of the duct. Airflow has several effects. Convection of the sound, which is present even in a uniform flow, produces the well-known Doppler shift in sound frequency and tends to decrease the attenuation due to a given wall impedance. Refraction of the sound, such as takes place in a boundary-layer shear flow, can either bend the sound field toward or away from the walls, depending on whether the sound travels with or against the flow. This behavior has a significant effect on the usefulness of acoustic liners.

An analytical model for the radiation of compressor and fan rotational noise from a circular duct with hard walls has been developed by Lansing. The duct has one open end which is unbaffled so as to resemble a type of jet engine inlet. The model gives an exact treatment of reflections at the open end and diffraction around the inlet lip.

A number of other models which are under development for the radiation of sound from ducts are illustrated in figure 25. The motivation behind this work is an improved understanding of noise transmission in and radiation from the inlets and fan discharge ducts of turbofan engines. P. E. Doak (Southampton University) developed an extensive theory based on a hard-walled rectangular duct of finite length with two open ends. The theory of Doak is being adapted to an annular duct by H. E. Plumblee of Lockheed. A. J. Martenson, of the General Electric Company, has developed a finite element representation of an axisymmetric duct of arbitrary cross section. The boundary conditions, for either hard or soft walls, are satisfied at a set of discrete points over the duct surface. This approach avoids the constraints of simple cross sectional and axial area developments. D. L. Lansing has developed a soft-walled annular-circular duct model which is representative of an acoustically lined long engine inlet duct with a large truncated center body.

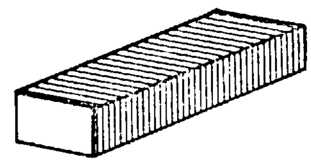
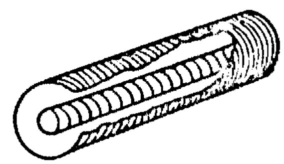
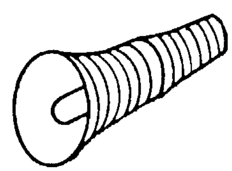
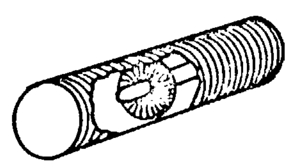
INVESTIGATOR	DESCRIPTION
DOAK	 FINITE RECTANGULAR DUCT
PLUMBLEE	 FINITE ANNULAR DUCT
MARTENSON	 VARIABLE CROSS-SECTION DUCT
LANSING	 CIRCULAR-ANNULAR DUCT

Fig. 25 DUCT CONFIGURATIONS FOR COMPRESSOR NOISE RADIATION

Duct Lining

Acoustic nacelle treatment has been found to be useful for alleviating fan engine noise. It has the advantage that it may be applied either in the development of new engines or in the modification of existing engines. This approach is illustrated in figure 26 which indicates the areas to which treatment might be applied to an engine. These areas include the inlet center body, concentric splitter rings, inlet wall, and all internal surfaces of the fan discharge ducts.

Two conferences were held in 1969, directly related to the duct lining problem (ref. 41 and 42). One of the conferences, ref. 42, resulted from NASA sponsored work with the Boeing Company and the McDonnell Douglas Corporation in which each company applied the duct lining technology to one of their production airplanes, a 707 and a DC-8, respectively. The projects were carried through to the flight test stage and both companies met their contractual goals, namely ~10 EPNdB by McDonnell Douglas and ~15 EPNdB by the Boeing Company. The beneficial results of this full-scale demonstration are readily apparent by examining figures 1 and 2, where the two latest airplanes by these two companies, the DC-10 and the 747, both satisfy the FAR-36 noise regulation.

Figure 27 shows some examples of the effects of wall impedance on mode shapes in a rectangular duct with one treated wall and no flow. The impedance was varied by varying the wall configuration as indicated in the sketches. The properties of the liner facing material and the characteristics of the air spring in the cavities behind the facing are significant in determining the impedance. The plots at the bottom of the figure

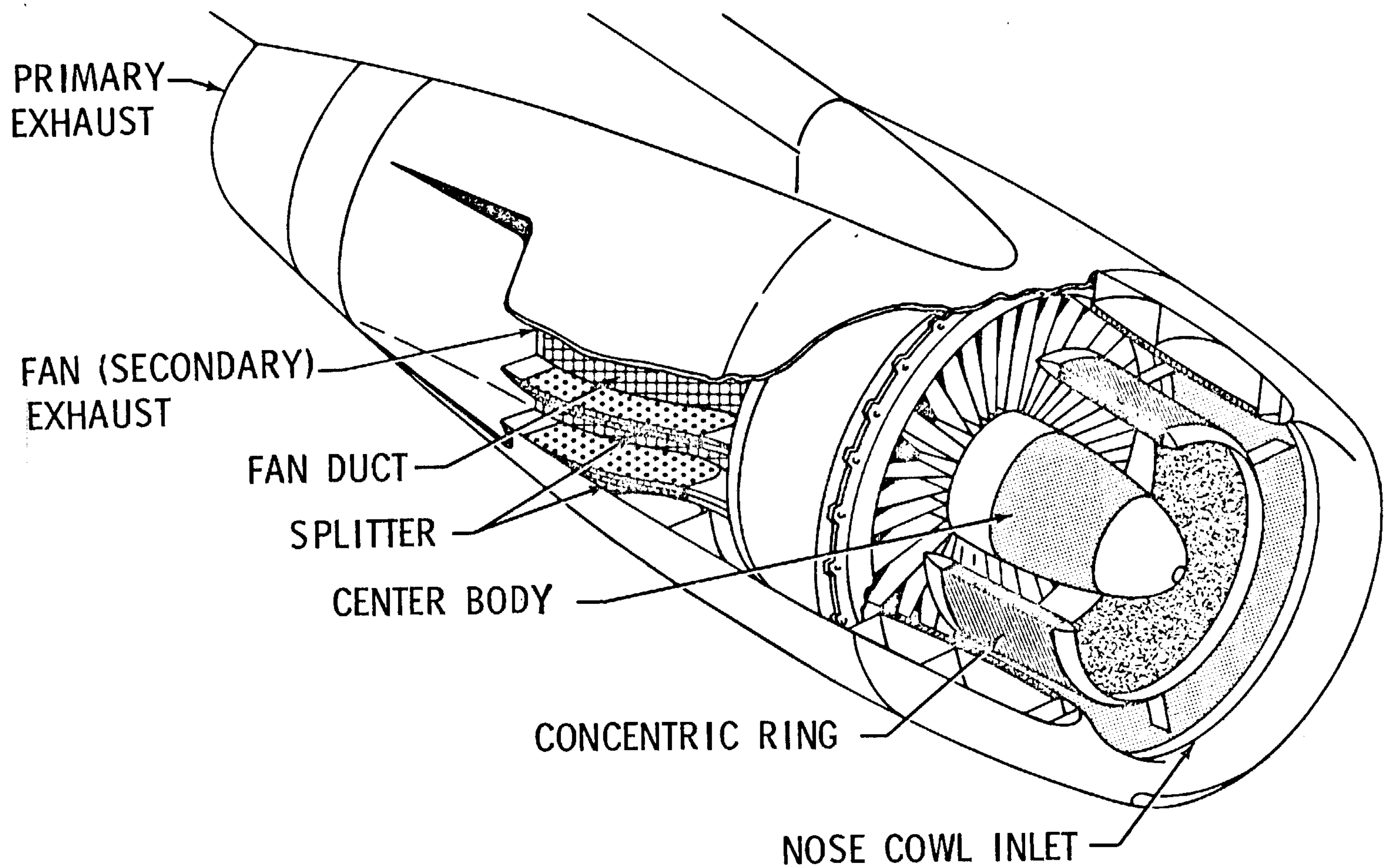


Fig. 26 DUCT ACOUSTIC TREATMENT OF FAN-JET ENGINE

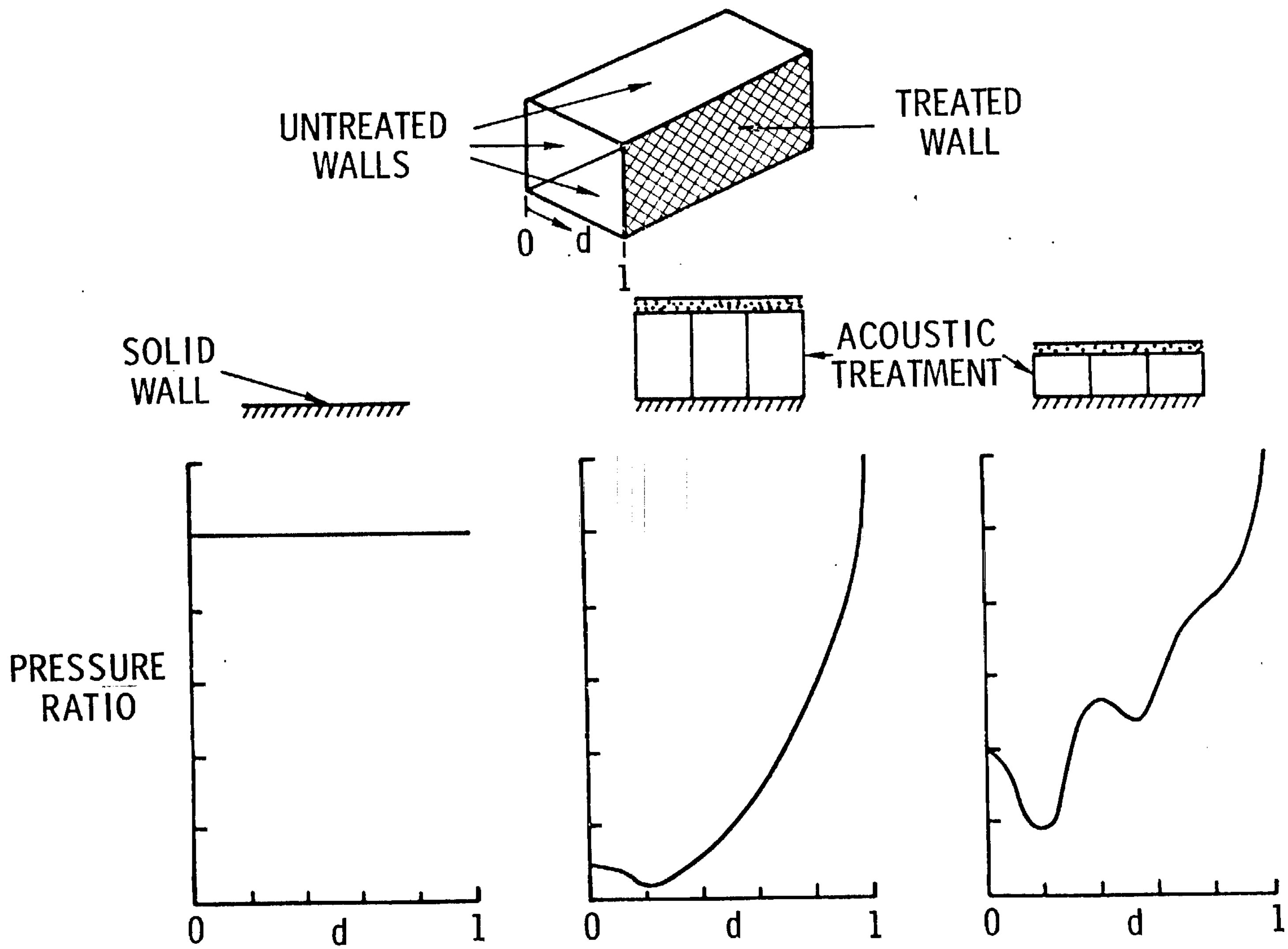


Fig. 27 EFFECT OF WALL IMPEDANCE ON DUCT MODE SHAPES

show the amplitudes of the pressure across the duct from the untreated wall to the treated wall. All of these plots relate to the mode which would be a plane wave if all walls were untreated as in the left-hand plot. The plots show the substantial distortions produced on this one mode by different wall impedances. These changes in mode shape are important because they affect the ability of this mode to transmit sound from a given source.

To summarize the effect of the duct and duct lining technology, linear analytical methods are now available for treating the noise emanating from ducts, with or without lining material. The critical issues revolve around the development of better lining material for the inlet as well as high temperature material for the exhaust, methods for handling the non-linear aspects of liner material, and increasing the band width capability of the lining material. A detailed program is given in the following outline.

5 Duct Acoustics

5.1 Influence of Duct Wall on Noise Transmission
Finite Ducts and (Static and Forward Flight)
Fore and Aft Transmission

- 5.01 Create known rotational noise (such as by properly timing speakers) and measure noise transmission and radiation
  - 5.011 Determine for various straight duct lengths.
  - 5.012 Determine for duct with various geometries - straight, bell mouth - lip geometry. Develop theory for variable geometry ducts - bell mouth.
- 5.02 Repeat 5.01 using as a noise source rotating blades with various stator arrangements.
  - 5.021 Investigate forward stator blocking and reflection.
- 5.03 Repeat 5.01 and 5.02 with non-uniform inflow and turbulence. Correlate noise with magnitude of non-uniform flow.
- 5.04 Measure vibration of duct wall.
  - 5.041 Determine noise transmission through wall and correlate with theory.
- 5.05 Inlet choking
  - 5.051 Practical and safe choking devices

5.1 Duct Liners

- 5.11 Acoustic Performance of Duct liner materials
  - 5.111 Static and with airflow
  - 5.112 Non linear effects development of analytical techniques

5.2 Optimization of Duct Liners for Acoustic, Aerodynamic and Structural Performance.

6 - PROPAGATION & OPERATION

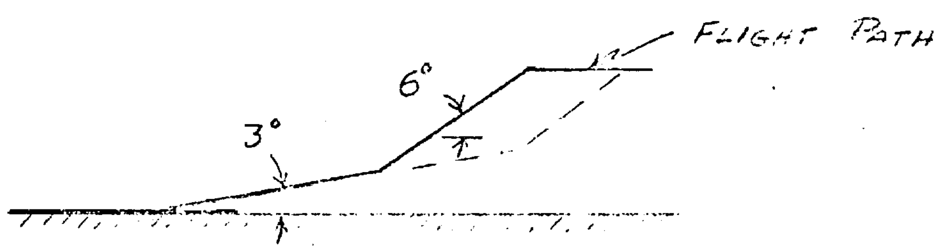
In addition to reducing the noise at the source as discussed in the previous chapters, large reductions in community noise may be obtained by changes in aircraft operating procedures for both landing and take off. Of primary importance is safety and any technique devised for noise abatement must, of necessity, be within the pilot's capability, not increasing the pilot's work load, particularly for instrument landings. Inherent in the noise received by the community is the propagation path, the influence of the atmosphere, the influence of ground and reflection and attenuation characteristics. This section is concerned with both the operational and the propagation aspects of the problem.

Operational Noise Reduction Techniques - In effecting a noise reduction through operation there are two major techniques--one is by increasing the distance from the source to the observer, and the second is by reduction of the source noise such as by reducing engine thrust. Other measures may also be taken of a more regulatory nature, such as changes in the flight path to avoid highly populated areas, or even restricted flights or curfew for specific hours. Here we shall restrict our attention to the distance and power reduction techniques.

Landing Noise Reduction Techniques

The nominal slope of current aircraft landing approach is 3°, and this system is standard throughout the world.

Numerous research flight tests have been made using other approach slopes, principally a 6° glide slope and combination of the 3° and 6° slopes as depicted below



where variations in the intercept altitude with the 3° glide slope was varied as indicated by the dashed line.

Typical examples of the test are reported in reference 43 and reference 44. Specific results for various landing techniques from reference 43 are shown in tables IV and V. The several approach profiles are shown in the first column of table IV, the glide slope angles are given in column 4, the transition altitude is given in column 5, and finally the type of guidance system and airplane characteristics are given in the remaining columns. The next table gives the results of the flight tests for the three measuring stations at 6520, 20,770, and 30,770 ft. respectively from the runway threshold. Various measurement units are also given in the table, but for comparison and consistency with the regulatory standards, we shall use only the integrated EPNdB unit. In general, approach profile H seems to provide the best overall reduction, providing -11.5 dB at static 1 and -15.6 dB at station 2. This profile involves a 6° approach to an altitude of 250 ft., then a transition to a 2.65 approach to touchdown. The problem with this scheme may be that the transition altitude (250 ft.)

AIRPLANE AND FLIGHT CONFIGURATION DATA

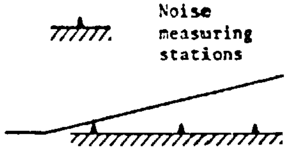
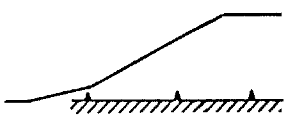
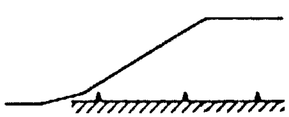
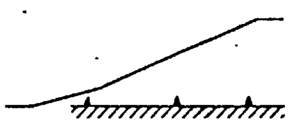
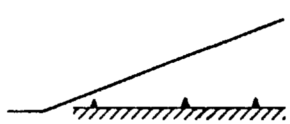
Profile	Profile	Run	Glide-slope angle, deg		Transition altitude, ft	Type of guidance	Flap setting, deg	Average approach velocity, knots	Airplane weight	
			Initial	Final			Main/auxiliary		Initial	Final
Noise measuring stations 	A	1 2 3	-2.65	-2.65	---	Single beam	40/10	117.5 118.5 118.5	175,200 172,000 168,900	174,400 171,200 168,100
	A-1	1 2 3					30/10	141 141.5 140.5	176,200 173,600 170,300	175,600 172,900 169,600
	G	1 2	-6.0	-2.65	400	Two segment, two beam	40/10	116.5 114	166,200 161,700	165,400 161,100
	G-1	1 2					30/10	138.5 137.5	165,200 163,300	164,600 162,700
	I	1 2				Single curved beam	40/10	114.0 107.5	159,600 154,600	159,000 148,500
	I-1	1					30/10	135	160,700	160,000
	H	1 2 3	-6.0	-2.65	250	Two segment, two beam	40/10	112.5 110 110	157,000 154,600 151,700	156,200 153,800 150,900
	M	1 2	-5.0	-2.65	500	Two segment, two beam	30/(-8.1 → 10) 30/(-9.4 → 10)	150 → 112 151 → 113.5	158,000 155,700	157,300 155,100
	L	1 2	-4.0	-4.0	---	Single beam	30/(-9.4 → 10)	150 → 114 151 → 114	153,300 150,800	152,700 150,100

TABLE IV

AVERAGED NOISE REDUCTION DATA

Station	Profile	Max dB(c), dB	PNLP, PNdB	PNLM, PNdB	PNLTM (FAA), PNdB	Integrated EPNL (FAA), EPNdB	Approximated EPNL (FAA), EPNdB
1	A	---	---	---	---	---	---
	A-1	---	---	---	---	---	---
	G	-2.4	-3.6	-3.1	-4.1	-4.5	-4.3
	G-1	1.8	.5	1.8	2.6	2.1	2.2
	I	.2	-.5	-.4	.4	.4	.2
	I-1	.2	-.9	-.1	-.5	.6	.5
	H	-12.6	-12.4	-14.7	-13.2	-11.5	-10.9
	M	-3.4	-3.9	-3.8	-5.3	-3.4	-4.3
	L	-12.2	-11.1	-12.8	-11.5	-9.3	-8.9
2	A	---	---	---	---	---	---
	A-1	---	---	---	---	---	---
	G	-10.5	-12.8	-14.6	-13.9	-16.2	-16.0
	G-1	-16.0	-17.1	-18.8	-17.4	-18.6	-18.6
	I	-10.8	-12.9	-13.4	-13.8	-10.9	-12.0
	I-1	-16.2	-16.0	-17.8	-17.2	-18.5	-18.2
	H	-12.8	-13.3	-15.0	-13.2	-15.6	-15.9
	M	-11.3	-10.6	-12.2	-11.7	-12.5	-12.6
	L	-9.2	-8.7	-10.3	-10.1	-8.8	-8.8
3	A	---	---	---	---	---	---
	A-1	---	---	---	---	---	---
	G	-3.0	-6.1	-5.9	-5.6	-3.7	-3.4
	G-1	-3.9	-7.3	-6.6	-6.1	-5.9	-6.0
	I	-3.1	-5.6	-5.2	-4.5	-6.3	-4.8
	I-1	-5.6	-9.6	-9.0	-8.2	-5.1	-4.6
	H	-2.1	-5.4	-5.0	-3.9	-6.2	-5.0
	M	-1.3	-2.8	-1.9	-1.6	-2.4	-1.4
	L	-3.9	-5.1	-4.9	-6.1	-3.4	-4.4

TABLE V

may be too low for safe operations in poor weather. A similar profile, but with the intercept at 400 feet, does not provide for a large reduction at station 1, being only -4.3 dB; however, at station 2, it is about the same as for profile H. Thus, very large reductions in landing approach noise may be obtained with a two segment approach. To obtain such reduction, however, would require world-wide acceptance of the system and the development of standardized landing aids to provide proper guidance during this critical phase of flight.

An ultimate objective should be the development of a completely automatic landing system together with an optimum minimum noise landing profile.

Take Off Noise Abatement Procedures - Various operational means are available for noise abatement during take off--the principal procedure is by means of a power cut back during the climbout. Reference 44 presents the results of flight tests of a Boeing 727 for a number of variations in power and flap settings. In table VI, seven different climb profiles are illustrated and described, where for the most part, variations in thrust and flap setting provide flexibility to achieve the various profiles.

The measured results from two of the climbout profiles are shown on figure 28, where the result of profile 2 is compared to profile 7. At station 2 there is about a 12 EPNdB reduction and about a 10 EPNdB at station 5. Thus a considerable reduction in noise levels may be obtained by proper use of engine thrust and flap setting.

CLIMBOUT PROFILES AND AIRPLANE OPERATING PROCEDURES

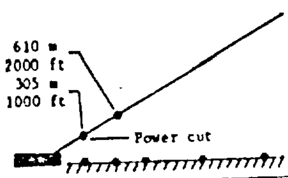
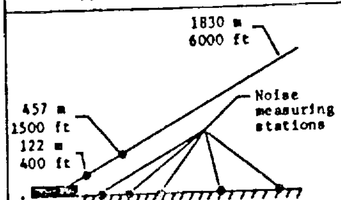
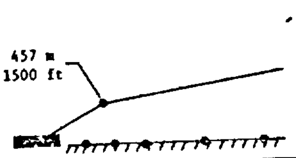
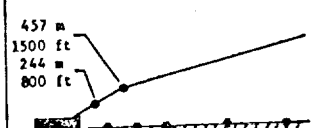
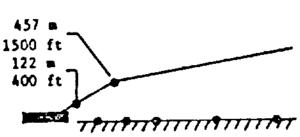
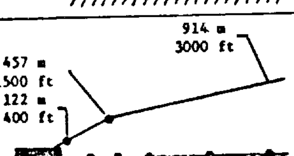
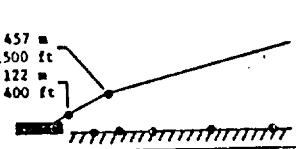
Schematic	Profile	Description of procedure
	1	Take-off power at V_2 + 10 knots with 15° flaps; at 305-m (1000-ft) altitude reduce power from take-off power to maximum continuous power, holding V_2 + 10 knots and 15° flaps; at 610-m (2000-ft) altitude retract flaps and accelerate as per schedule. (Deck angle limitation, 15°.)
	2	Take-off power at V_2 + 10 knots with 15° flaps; at 122-m (400-ft) altitude begin reducing to 0° flaps as per schedule and accelerate to 210 knots; at 457-m (1500-ft) altitude reduce to maximum continuous power and accelerate to 220 knots; at 183-m (6000-ft) altitude continue smooth acceleration to 250 knots and maintain stabilized power.
	3	Take-off power at V_2 + 10 knots with 15° flaps; at 457-m (1500-ft) altitude reduce power to that required for 152-m/min (500-ft/min) climb rate with 15° flaps and speed attained at end of segment 1; maintain this speed and configuration. (Deck angle limitation, 15°.)
	4	Take-off power at V_2 + 10 knots with 15° flaps; at 244-m (800-ft) altitude. begin retracting flaps as per schedule; at 457-m (1500-ft) altitude reduce power to that required for 152-m/min (500-ft/min) climb rate with 2° flaps and maintain.
	5	Take-off power at V_2 + 10 or 20 knots with 15° flaps; at 122-m (400-ft) altitude retract flaps to 5° and add 10 knots to climb speed; at 457-m (1500-ft) altitude reduce power from take-off power to power required for 152-m/min (500-ft/min) climb rate, holding V_2 + 10 or 20 knots and 5° flaps; maintain these conditions until 914-m (3000-ft) altitude is reached, then proceed SOP climb not to exceed 210 KIAS. (Deck angle limitation, 15°.)
	6	Take-off power at V_2 + 10 or 20 knots with 15° flaps; at 122-m (400-ft) altitude retract flaps to 5° and then to 2° prior to reaching 457-m (1500-ft) altitude; at this altitude reduce power from take-off power to power required for 152-m/min (500-ft/min) climb rate, holding airspeed and 2° flaps; upon reaching 914-m (3000-ft) altitude proceed SOP not to exceed 210 KIAS. (Deck angle limitation, 15°.)
	7	Take-off power at V_2 + 10 knots with 15° flaps; at 122-m (400-ft) altitude begin retracting flaps as per schedule and accelerate to 210 knots; flaps are to be at 0° prior to reaching 457-m (1500-ft) altitude; at this altitude reduce power to that required to maintain 1.5 positive gradient with one engine inoperative (approximately 91-m/min (300-ft/min) climb rate at 210 knots with one engine inoperative); maintain at 210 knots.

TABLE VI

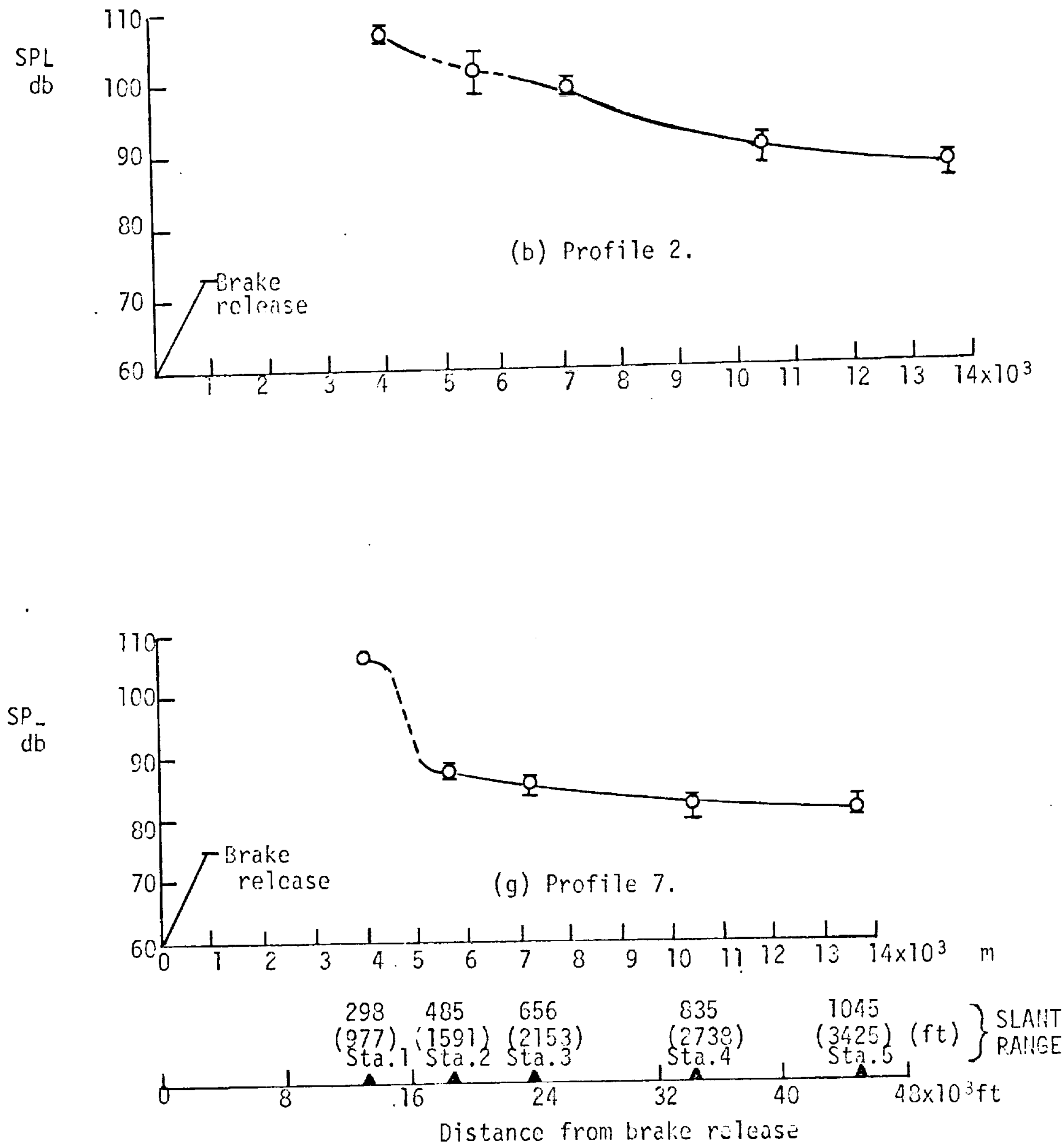


Fig 28. Average values of sound pressure level measured along ground track of airplane for two climbout profiles. Dash lines represent range in which power reductions were made.

Propagation

The noise received at a distant point on the ground from an aircraft during the take off roll down the runway or during flyover is influenced by many factors. These factors include temperature, winds and gusts, turbulence, and terrain. In addition, sound is attenuated in its passage through the atmosphere due to the molecular absorption which is a function of temperature, humidity and frequency. The corrections for molecular absorption have been determined under laboratory conditions and are accurate under those controlled conditions. However, when these corrections are applied to actual aircraft noise, rather large discrepancies are found. This fact then makes it difficult to comply with the FAA certification requirements under the usual variable atmospheric condition that exists when a new aircraft is being certified.

Typical of the effect of the variable atmosphere and terrain are results reported in reference 45, figure 29, which illustrate the magnitude of the problem. Here excess attenuation in dB's is plotted against frequency. Excess attenuation means that the standard method of predicting the noise at a given distance was used, including the $1/R^2$ distance effect and the molecular absorption coefficients for each frequency, and the plot reflects the difference between the predicted and actual noise. For instance at 250 Hz, at distance $>$ 2000 m, the actual measurement of noise from an aircraft was 25 dB below the predicted value. Two main results can be deduced from examination of figure 29. For frequencies above 1000 Hz, the theory underpredicts the noise levels and, since the human ear is highly sensitive to frequencies in the 2000 - 3000 Hz range, this represents a serious discrepancy. The reason for these differences is not known and represents an area of needed research.

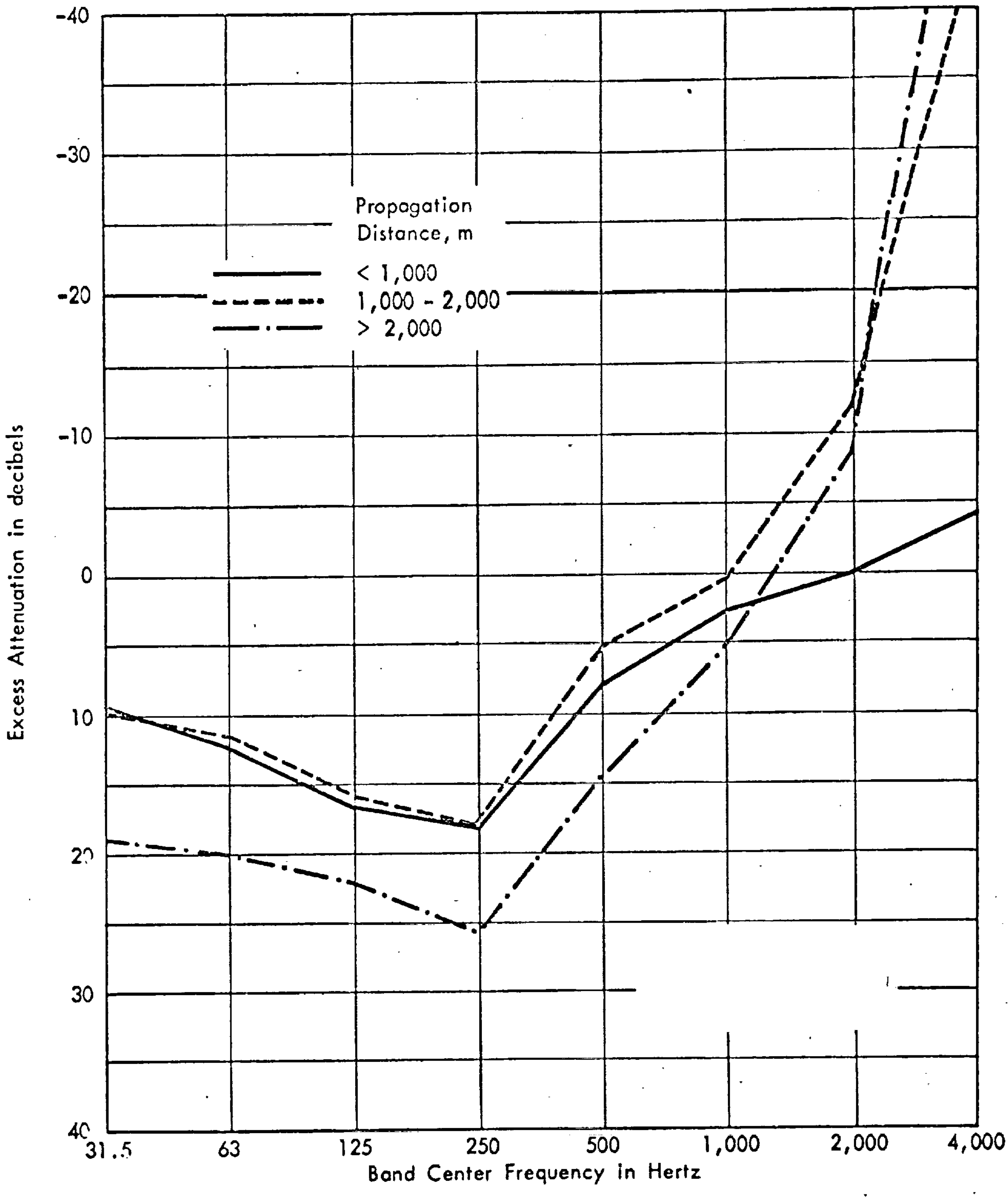
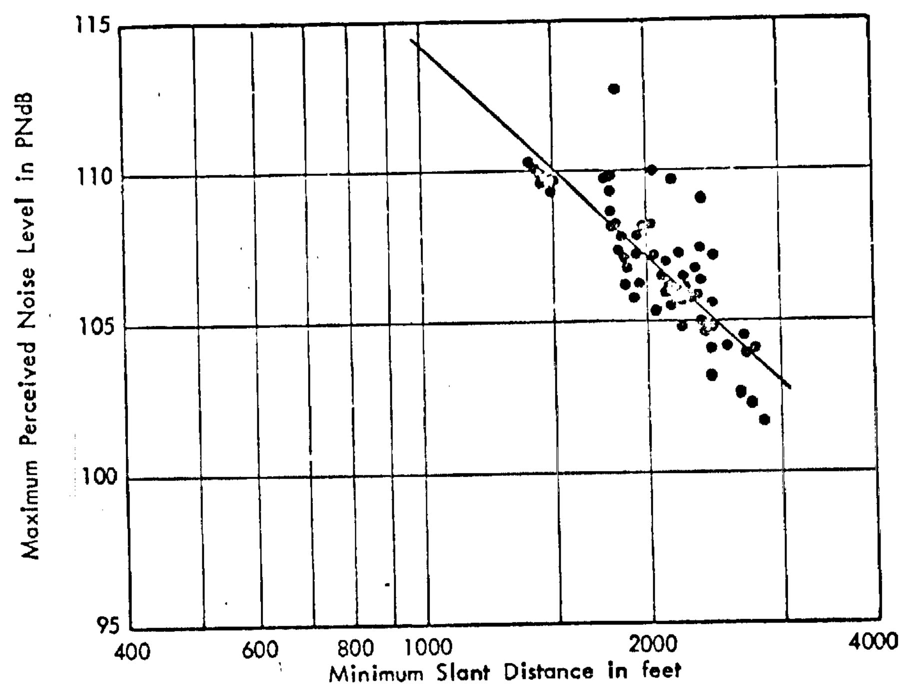


Fig. 29 MEAN VALUES OF EXCESS ATTENUATION

Wind Speed Less than 5 m/sec -- Standard Attenuation Included

Another example of the effect of the atmosphere is shown in fig. 30 from ref. 46 where PNdB is plotted against distance from the aircraft for a 4 engine turbojet aircraft. All of these flights were made during one day of operation during which the weather conditions were fairly constant. A variability of about 6 dB was found in the 1000 ft. slant range data. Again, the reason for this variability is not known, other than "variable weather conditions."

In summary, then, we can state that the"standard" method for correcting noise measurement needs considerable research to account for the low and high frequency discrepancies, and that weather variability can account for as much as 6 dB difference between similar flights under atmospheric conditions which one might term "fairly" constant. A detailed program for research is given in the following outline.



FOUR-ENGINE TURBOJET AIRCRAFT

Fig. 30 VARIATION IN MAXIMUM PERCEIVED NOISE LEVELS (PNLM) AS A FUNCTION OF MINIMUM SLANT DISTANCE

6 Propagation and Operation

6.11 Evaluate temperature, relative humidity, turbulence effects on noise propagation in real atmosphere.

6.12 Statistical survey of low altitude atmosphere conditions.

6.13 Ground reflection effects

6.14 Improved prediction of air to ground noise propagation for large distances.

6.15 Evaluation of flight operating conditions.

7 - STRUCTURAL RESPONSE

An understanding of noise induced structural responses is significant in such problems as the internal noise of flight vehicles due to boundary layer excitation of the external skin surfaces; the responses of turning flaps in a jet exhaust stream, both from the standpoint of structural loads sonic fatigue and associated noise radiation; and the noise radiated through the case structures of a jet engine due to internal noise loads.

Significant factors are the vibrational characteristics of the structures which involve a skin surface and supporting elements; the definitive features of the noise field such as frequency spectra, intensity levels, and correlation areas; and the coupling interactions with the airflow adjacent to the impinged surface. Also involved are statistical concepts of loading due to complex fluctuating pressure fields and responses of complex structures.

Current knowledge of the response of nonhomogeneous structures to complex noise fields is fragmentary and new methods must be developed for predicting transmission losses through fuselage structures and for predicting the dynamic responses and fatigue lives of built-up structures exposed to intense acoustic loading.

The main problem is the development of satisfactory methods for designing flight structures to withstand intense acoustic loadings. There is a need for careful analytical and experimental studies and for incorporation of improved techniques into computer aided design procedures.

Analytical methods will be developed to predict and describe the dynamic pressure loadings, the manner in which the combined acoustic and airflow environment couples with the structure, and the resulting structural response. Extensive use of statistical concepts is anticipated.

Initial experimental structural response and materials work will be accomplished in high intensity noise facilities within which the noise and temperature environment can be varied under close control. For some experiments in which boundary layer noise loadings are involved, specialized wind tunnels with particular attention to tunnel noise contamination and to boundary layer thickness considerations will be used. Such wind tunnel tests will be used for definition of the dynamic pressure loading patterns as well as to study the coupling of these loads with the structure.

Also needed are definitive fluctuating pressure and structural response measurements involving flight vehicles and for high Reynolds number flow conditions.

The critical issues in structural response are:

(a) To provide methods for design of aircraft structure to withstand sonic fatigue with minimum weight or other penalties.

(b) To develop methods for predicting and reducing structurally transmitted noise.

(c) To incorporate optimum fatigue and transmission design techniques into computer aided aircraft structural design procedures.

(d) To define the noise loads due to aerodynamic boundary layers for a range of operating conditions. A detailed program is given in the following outline.

7 Structural Response

7.1 Subsonic

- 7.11 Engine case loads and response prediction
- 7.12 Acoustic material fatigue properties
- 7.13 Prediction of fluctuating loads due to airflow-surface interaction
- 7.14 Response of built up structure to noise loads
- 7.15 Fuselage noise transmission

7.2 Supersonic and Hypersonic

- 7.21 Prediction of boundary layer noise loads
- 7.22 Prediction of dynamic response of structure to boundary layer noise
- 7.23 Elevated temperature sonic fatigue (subsonic and supersonic)
- 7.31 Cockpit noise control

8 - HUMAN RESPONSE

Problems concerned with responses of people to aircraft noise may be grouped into three categories: Those dealing with responses of people in communities near airports, those concerned with the ground crews at the airports and those involving the crew and passengers in the aircraft. Underlying each of the noise problem categories is the need to further the understanding of interrelated multidisciplines of physics, engineering, psychology, and associated human factors. Although there are responses which are generally common to the three groupings there are basic differences. The airport ground crew may be exposed to very high noise levels which require ear protection to prevent hearing loss or ear damage. Similarly the flight crew and passengers may be subjected to levels which cause hearing loss. Also for the flight situation the noise may be combined with adverse vibrations which result in an environment which is discomforting and degrading of task performance. Although problems of possible hearing loss or task performance interference due to noise in the airport community have not been thoroughly investigated and documented, the problem of annoyance due to the intrusion of take off and landing noise has become of national concern as a major obstacle facing our air transportation system. Therefore, the main thrust of programs to alleviate aircraft noise is directed to obtaining aircraft whose operational noise is generally acceptable to the public and does not degrade the environment of those living near the airports.

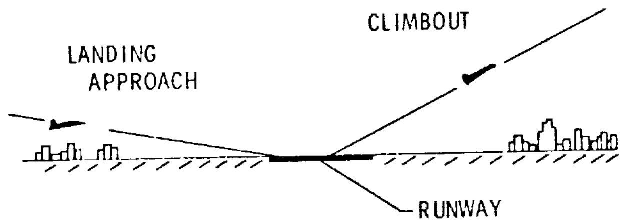
The aircraft noise problem in the community is especially demanding on government programs because unlike the ground crew problem or the aircraft interior problem, the aircraft noise in the community intrudes upon people who are generally third party to commercial aviation - they are neither in direct control of the noise sources nor are they direct benefactors of the aviation operations.

Because noise is not solely a physical quantity and is dependent upon the reactions of the receiver, the development of a meaningful measuring unit to quantitatively describe aircraft noise is an important challenge. In addition to measuring the noise of aircraft is the requirement for measuring community noise exposure and for properly accounting for human attitudinal parameters along with environmental parameters which affect the acceptability or unacceptability of the noise. Thus, there is important need for human response to noise research in defining acceptable aircraft noise and airport community noise exposures.

The needs for such measurement units are as follows. Accurate units are desired for use in the systematic design of quieter aircraft to meet noise specifications and in various aspects of aircraft noise certification. Units which are simple in concept and easy to use are needed in connection with the prediction of community annoyance and complaint patterns, land use planning near airports, and airport traffic monitoring and control. It is, of course, desirable to have one measurement unit that would be adequate to fill all these needs.

In figure 31 are indicated the nature of the airport noise problem in communities near airports and the significant factors in noise-induced responses. Noise is a problem because of the low-altitude operations of aircraft in landing approach and in take-off and climbout operations. Of particular significance are the psychophysiological characteristics of people which are significant in their responses to noise, as well as the physical characteristics of the aircraft noise stimuli. Also of importance in most cases are such factors as the nature of the airport traffic, including the use of preferential runways, the mix of aircraft types, and flight scheduling; and community environment considerations, including background noise levels, economic factors, and types of community activities.

It is known that a person may respond to noise in various ways as indicated in figure 32. Such responses as subjective annoyance, speech interference, sleep interference, degradation of task performance, and hearing loss are identified, and the significant ranges of noise level for each response are indicated. (See ref. 47). One of the obvious results from such response studies is the wide variation among people in the way each responds to noise. This accounts at least in part for the wide range of significant levels. All these responses may be important in real life. Each has been studied separately in laboratory situations and, as a result, subjective annoyance responses are judged to be of particular importance in airport community situations. The measurement units discussed in the remainder of this section are those which relate to subjective annoyance and which include considerations of the physical characteristics of the noise and the psychophysiological characteristics of people.



- CHARACTERISTICS OF PEOPLE
- AIRCRAFT NOISE CHARACTERISTICS
- AIRPORT TRAFFIC
- COMMUNITY ENVIRONMENT

Fig. 31 FACTORS IN AIRPORT COMMUNITY NOISE

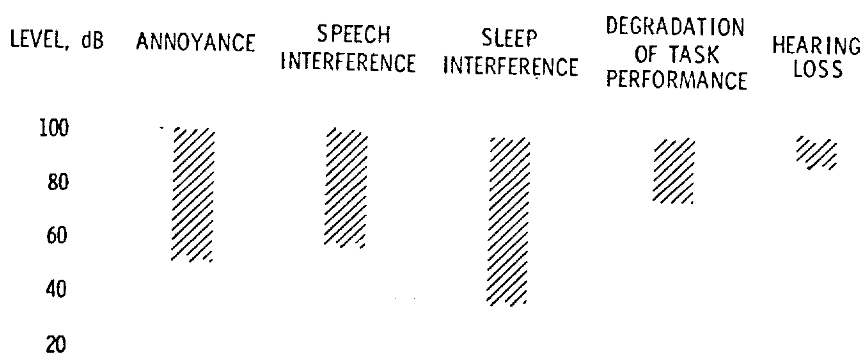


Fig. 32 RESPONSES OF PEOPLE TO AIRCRAFT NOISE

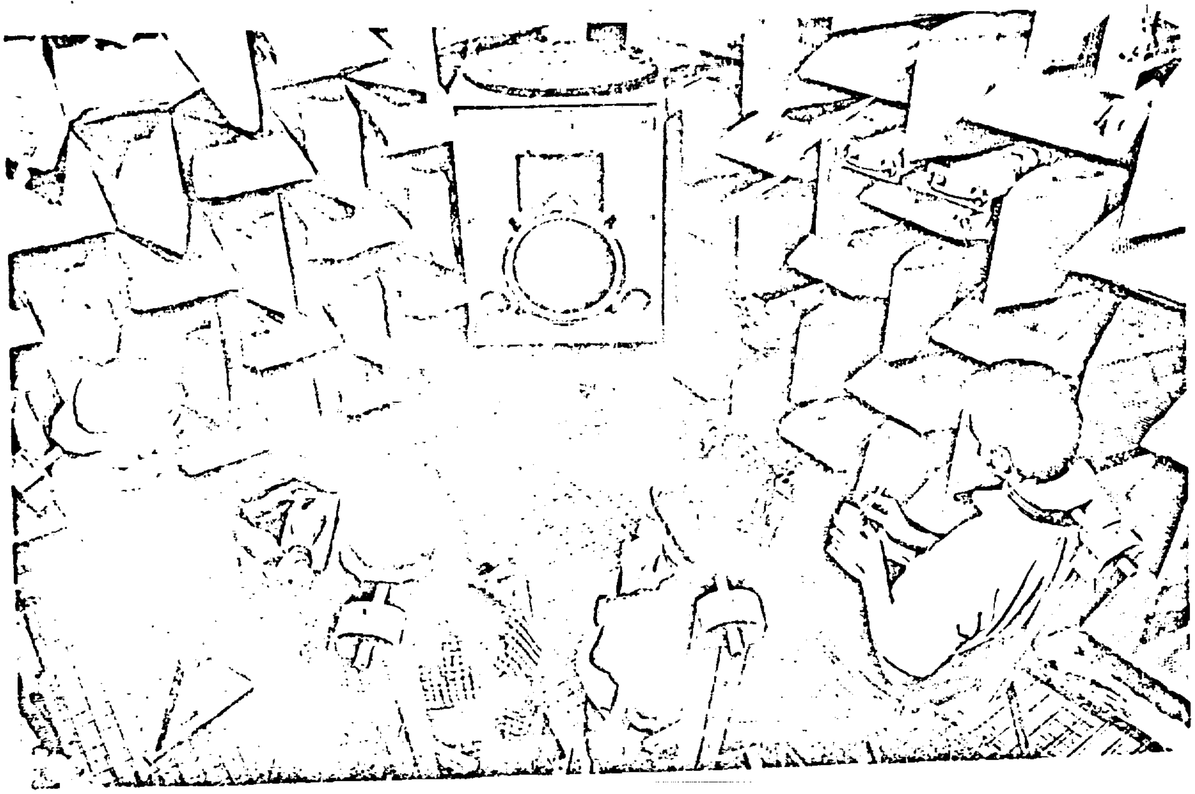


Fig. 33 LABORATORY TEST SETUP

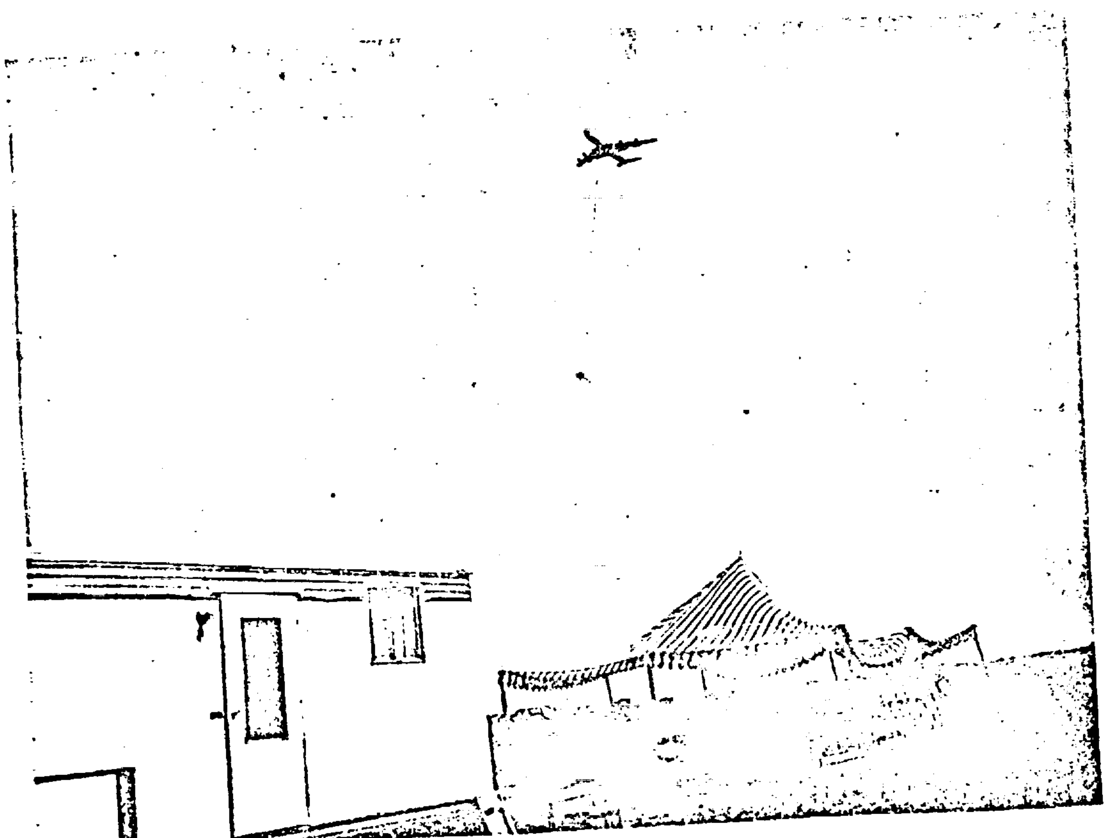


Fig. 34 MOSES LAKE FLYOVER TEST SETUP

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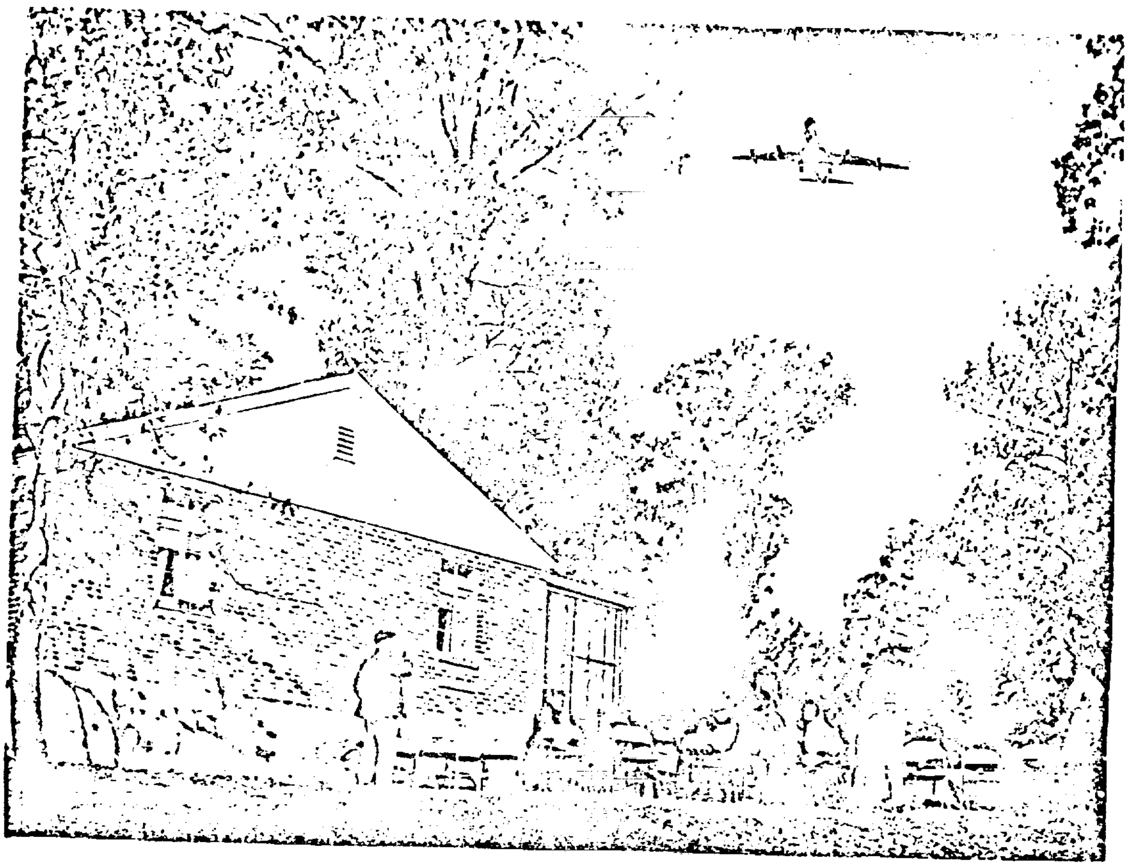

Fig. 35 WALLOPS FLYOVER TEST SETUP

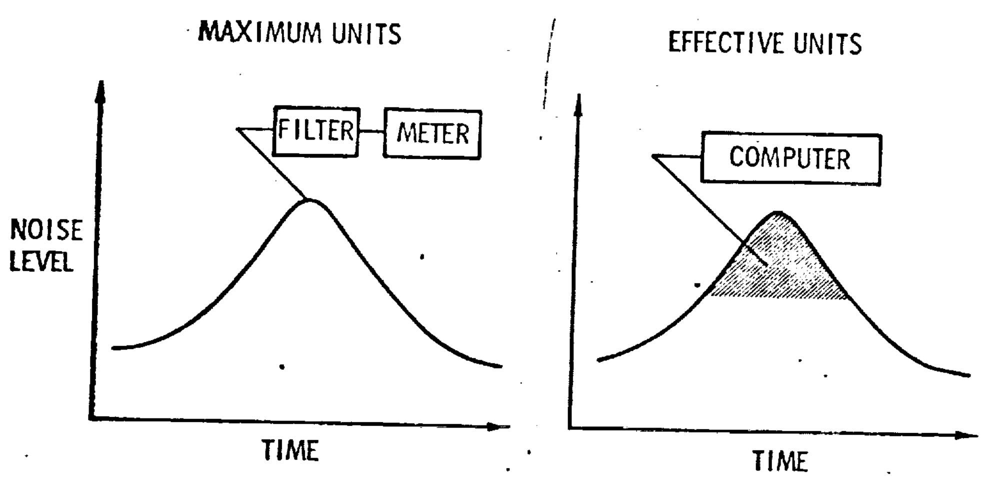

Fig. 36 TYPES OF MEASURES FOR AIRCRAFT FLYOVER NOISE

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In the development of subjective annoyance units, studies to date have been limited to a few test situations where the environment could be controlled. One example situation is shown in the photograph in figure 33, which was taken in a laboratory of Bolt Beranek and Newman, Inc. (See refs. 48, 49, and 50). This is a small anechoic room having wall treatment such that echoes are eliminated. A loudspeaker system is provided for playback of aircraft noise signals, and the people are arranged in a manner suitable for obtaining comparative subjective judgments of the noises. The advantage of such an experimental setup is that many of the factors in the tests are under very close control. The disadvantage, however, is that the environment for the subjects is lacking in realism.

Another type of study is illustrated by the photographs in figures 34 and 35. Figure 34 shows one of the test sites of the Moses Lake flyover experiments involving Boeing 707 airplanes. (See ref. 51). A standard Boeing 707 airplane was compared with a similar airplane modified to reduce its approach noise levels by means of nacelle acoustic treatments. Subjects were grouped both outdoors under awnings and inside of house trailers for purposes of making subjective judgments.

Figure 35 shows the test setup for similar studies at the NASA Wallops Station. (See ref. 52). For these studies about a dozen different aircraft, including helicopters, were used, and juries of subjects were located both outside and inside resident-type structures for subjective reaction studies. Although it is realized that such studies as those illustrated in figures 34 and 35 do not completely represent real-life situations, they are more realistic than those of figure 33.

Two general types of annoyance measurement units for flyover noise exposure are illustrated in figure 36. The noise exposure consists of a transient signal which varies in noise level as a function of time in a manner suggested by the curves in the figure. The two types of units are characterized as maximum units and effective units. The maximum units are determined with the aid of a filter with appropriate weighting features plus a direct-reading meter. The function of the filter is to provide an appropriate frequency weighting to represent the annoyance value of the noise. The significant meter reading is the maximum value. With regard to the effective units the significant values are determined by a more sophisticated data analysis which is performed by a computer and takes into account the significant features of the entire time-history exposure.

These noise evaluation units can be further categorized as follows:

Characteristics of people Noise characteristics Levels	Maximum units ("A-scale," PNL, etc.)	
Spectra Tones Duration Time history		Effective units (EPNL)

The maximum units include such units as "A-scale" and PNL (perceived noise levels), which along with about 10 other similar units can be properly filtered by a frequency-weighting network. These units are designed to account for the psychophysiological responses of people to noise and to account for such features of the noise as levels and spectral content.

The effective units, on the other hand, are designed in such a way as to account for such additional features of the noise as its tone content, the duration of exposure, and other aspects of its time history. An example of such effective units is the EPNL (effective perceived noise level). In studies to date about 2 or 3 dozen different effective units have been evaluated and these, in general, are related to the basic concept of effective perceived noise level.

In order to evaluate the two types of measurement units, the results of a number of recent studies are summarized in figures 37 and 38. (See refs. 49 and 51 to 56). Data from a number of different studies, as indicated by the letters A to E, are included in figure 37 for both maximum units and effective units. Each of the symbols represents the results of a separate evaluation test of a particular measurement unit. For each of these tests hundreds, or sometimes thousands, of judgments were made and the results were identified with a standard-deviation value. If perfect agreement had been obtained between the judgment data and the predictions based on physical measurements of the noise signal, the data points would be on the zero line. Obviously, perfect agreement was not obtained for any of the units studied.

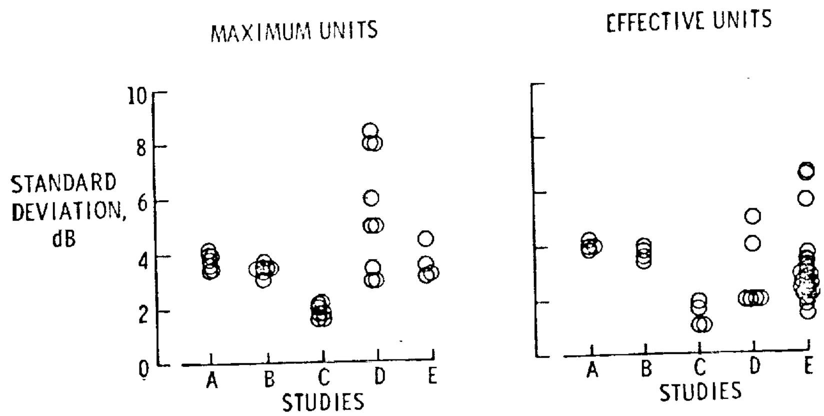

Fig. 37 RESULTS OF LABORATORY STUDIES

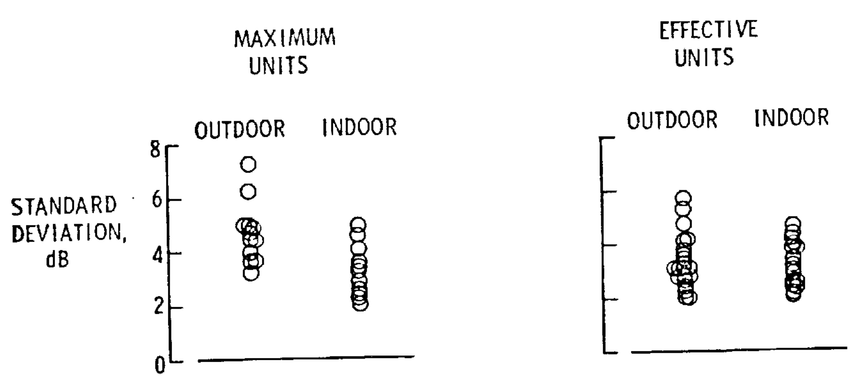

Fig. 38 RESULTS OF WALLOPS FLYOVER STUDIES

The units for which the smallest standard deviations were obtained are the ones of greatest interest. It can be seen, in general, that the best effective units are more accurate than the best maximum units.

Similar data from flyover studies are shown in figure 38. (See ref. 57). The data are presented in the same format except that results are included for both indoor and outdoor observer situations. These data, which were obtained in the Wallops Station flyover studies, are in general agreement with those of figure 37 , and the accuracies are comparable. Although data from the Moses Lake flyover tests (ref. 58) are not available in a form convenient for plotting in figure 38, the results are judged to be generally consistent with the data in figure 38. An additional conclusion reached from the studies of reference 58 was that the observed flight noise reductions (due to acoustic treatment of engine nacelles) were in general agreement with noise reductions predicted from ground-based measurements.

Recent studies to evaluate noise measurement units have been summarized and the general status of units categorized as maximum and effective has been discussed. It is indicated that maximum units are simple in concept, simple to use, and require a minimum of electronic equipment for measurement and analyses. They are thus judged to be adequate for most planning and monitoring functions regarding noise around airports. The effective units, on the other hand, are noted to be more sophisticated in concept and more cumbersome to use. The electronic equipment involved is more sophisticated in concept and more cumbersome to use. The electronic equipment involved is more sophisticated, bulkier, costlier, and requires expert operators. Effective units have important use in the development and design of quieter aircraft and in the noise certification of aircraft.

The subjective units, dB(A), PNL and EPNL, are aimed at defining the annoyance characteristics of the individual for one event. The CNR was derived to define the annoyance of one individual due to a number of recurring events. However, none of these units address the general problem of the total society, for instance, what is the benefit or disbenefit to a group of the presence of an airport in a given community. At the present time there is almost a world wide moratorium on the construction of new airports; the local communities near which a new airport would be located have managed to stop the construction of new airports. Therefore, an attempt should be made to quantitize the nuisance of an airport and relate that to the benefit that an airport has to a local community. Richards (ref. 59) has attempted to provide a first step in this direction by developing a disbenefit/benefit ratio which we shall term the Richards Number. An example of the application of his concept is shown on fig. 39, where the disbenefit/benefit ratio is plotted against years. First note that Heathrow is listed as having a value of 1.61 which correlates with the high complaint record from person living around this airport. Luton airport (the second London airport) will have a value of D-B of .67 in 1980. However, if the runways were realigned, this would reduce

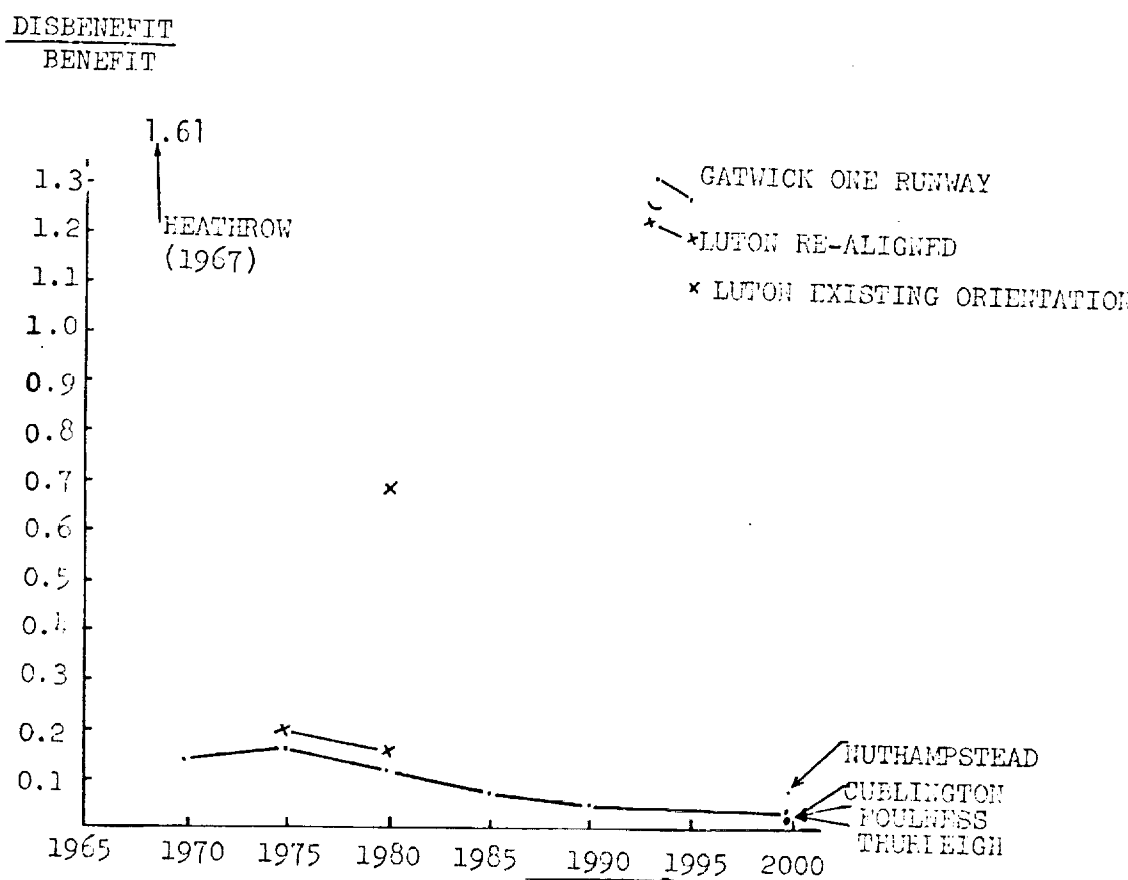

Fig. 39 D-B ratio for a range of UK airports

to a value of .18. Thus the Richards number could be a very valuable criterion in the location selection process of new airports as well as in assessing the benefit or disbenefit of changes in existing airports. Further research in this direction should be pursued.

The current state of the art is such that many units of measure have been developed and found somewhat adequate as descriptors of both aircraft noise and airport-community noise exposure. Because reduction of aircraft/airport noise is technically difficult to obtain within practical limitations of safety and economics, there is important need to advance the state of the art and to keep the measurement methodology abreast of advanced aircraft development and changing attitudinal characteristics of the people. A resulting unit, EPNdB, has been judged adequate for initial implementation of noise certification of currently produced CTOL's.

It has been recognized that current aircraft noise certification levels may in the future be revised to lower levels of acceptance or may be restructured using advanced units of measure when technology for doing so is in hand. Research to advance this technology is essential to aircraft noise regulation and to effective noise certification of aircraft.

Thus for CTOL aircraft the state of the art is such that newly constructed aircraft are being certified to meet noise standards which are below the noise levels of the existing commercial fleet. A major problem concerns the existing fleet and the potential benefits of acoustically retrofitting these aircraft. This retrofitting will require considerable costs associated with research and development in addition to hardware changeover expense. Therefore, there is important need for meaningful assessments of the noise alleviation benefits to be obtained from a retrofit program and the associated economic tradeoffs. Currently retrofit research and development of retrofit systems for the 707, 727, DC-8, and DC-9 are underway and the need to evaluate the retrofit benefits in terms of community acceptability is upon us. Subjective evaluation study results to be obtained by Dr. Paul Borsky at Columbia University (under NASA Grant) are expected to contribute to milestone decisions by the DOT/FAA on retrofit rule making.

The retrofit program is placing renewed importance in the need for further development of subjective noise measurement units. Much of the research to date has been accomplished in special acoustic laboratories such as anechoic rooms where test subjects were solely concerned with passing judgment on the annoyance on acceptability of loudspeaker presented playbacks of aircraft noise. Although these researches have proven efficient and effective in obtaining an assessment of aircraft noise, there are important shortcomings in relating these test results to the real life situation. Thus, there is the need to obtain data under controlled laboratory conditions which are more representive of the real life situation. Among the recognized conditions which are important are that the subject be in a normal everyday type environment, be involved in everyday activities, and be exposed to noise stimuli which authentically sound like an aircraft flying by. The merits of various methods of judging noise annoyance have only been initially investigated. Further work is needed to relate the results from paired comparison tests with those from magnitude estimation tests. Other judgment methods must be explored to assure that the most meaningful judgments are obtained. The specialized capability of the Aircraft Noise Reduction Laboratory scheduled for research operation by 1974 at the Langley Research Center is cited as a milestone in providing real life type testing in a laboratory.

The concern for CTOL noise has emphasized the annoyance aspects of aircraft flying over airport communities with limited attention to the intrusion of the noise into periods of rest or sleep.

It is readily recognized that awakening due to aircraft noise is unacceptable and some data have been obtained to evaluate the noise levels where awakening may occur. However, there is considerable to be learned in regard to wide ranges of sleep awakening thresholds among individuals. Also it is recognized that aircraft noise need not awaken one to intrude upon his sleep. Limited data have been obtained to relate aircraft noise levels with changes in levels of sleep. Initial data have indicated that the non-awakening intrusions can have an after effect on the victim's ability to perform a task. Assuming continuing growth of round-the-clock commercial aircraft operations to more efficiently utilize fleet aircraft, there is need for additional understanding to control the intrusion of aircraft noise into man's sleeping hours.

The intrusion of CTOL noise into man's everyday activities is recognized as a potential detriment to his performance of tasks - whether they be occupational tasks, household activities, or recreational participations. For the airport-community situation information on interference with task performance is not well in hand as research into this subject has only begun. The importance of the close interrelation of noise judgment and the activity engaged in is recognized as an important element in judging the annoyance of aircraft noises.

Sociometric studies of airport communities have shown that attitudinal parameters share with noise exposure in importance in contributing to annoyance created by aircraft. For example, in studies of 9 airport communities (Tracor), the attitudinal parameter of "fear" was found to outrank noise exposure as a prediction of aircraft noise annoyance. To date community survey studies have revealed important socio-economic factors associated with acceptance of aircraft noise exposure. These studies have developed additional insight into the airport-community noise problem and the findings are expected to be useful to land use planners, airline operators, airport operators, government regulatory groups, etc. in alleviating the annoyance impact of aircraft operations on communities. For example, these studies have led to the use of an improved "dynamic" preferential runway system (DPRS) at JFK which is designed to limit the overflight dwell time for each community sector in accordance with annoyance predictions. Initial assessment of this system shows considerable potential and the need for further development and evaluations. Evaluation of this system at JFK is cited as a milestone which may point the way for DPRS installations at many airports.

Initial sociometric surveys were conducted at the very beginning of an era where there is a growing concern for environmental quality. Because of the changing attitudes and growing adverse feeling regarding pollutants of all types, it is recognized that attitudinal parameters associated with aircraft annoyance in the community may be undergoing change also. Thus, there is an important need to keep the understanding of airport-community attitudes abreast of the changing times and to properly control the noise exposure so that aircraft operations do not unduly intrude into the community environment.

In addition to the airport-community, CTOL operations must also be acceptable to the airport ground crews and to the occupants within the aircraft. There are basic noise studies concerned with shifts in threshold of hearing and with ear damage. In general much has been done in both of these areas; however, there is need for information specifically related to detrimental effects of aircraft type noise stimuli. Apart from auditory effect of aircraft noise, there is little information available on effects on crew performance and on ride comfort. Today's CTOL aircraft are equipped with auxiliary power units (APU) which are impressive noise sources - equivalent to the main power plants of yesteryear's aircraft and thus there is a need for further evaluation of noise generated by auxiliary power units.

For STOL type aircraft, the state of the art is largely dependent upon the technology developed for the CTOL type aircraft. However, because the STOL vehicle is quite different in its power plant systems and in its use of lift augmentation, there are sources of noise having characteristics different from those of CTOL noise. In addition the STOL type aircraft may be expected to be operated quite differently than the CTOL; therefore noise exposures from STOL operations must be considered differently.

In general STOL aircraft will be expected to generate considerably more acoustic energy at frequencies below 300 Hz. Work by Dr. Karl Kryter (under NASA contract) has indicated that the noise at these lower frequencies should be handled differently in the calculation of perceived noisiness. The full impact and validity of the proposed modification to the calculations remains to be explored. These calculations of perceived noisiness involve only the auditory effect of the low frequency noise whereas the non-auditory responses, about which little is known, may be of foremost importance in evaluating public acceptance of STOL type noise. Because building structures generally respond to subaudible or near subaudible frequencies, there is need for additional information to define and evaluate indoor environments which may result from STOL operations.

The indoor environment situation may be especially important for STOL aircraft because of their frequent operations relatively close to urban buildings. Thus, the need for additional information on STOL type noise as it may affect task performance and sleep activities is evident. Also associated with STOL operations are background noise environments which are somewhat different from those experienced with CTOL aircraft. Initial studies by Boeing-Vertol (NASA contract) have indicated that presently used duration corrections in EPNdB calculation may be excessive for longer durations of noise.

The concern for the noise environment in the interior of the STOL aircraft again must draw heavily on experience with CTOL aircraft operation. However, additional information is needed to define the interior environments resulting from STOL type noise sources and from the transmission characteristics of STOL aircraft construction. In evaluating the effects of this interior environment, the combined acoustic and vibration environments associated with STOL aircraft may result in responses somewhat different than those involved in assessing the ride quality of CTOL aircraft. The need here is for overall ride quality information and for a determination of acceptable criteria for acceptable ride comfort. The use of the QUESTOL vehicle in flight tests to study noise acceptability of STOL aircraft is cited as a milestone.

For the VTOL type aircraft the state of the art is based on limited experience with commercial VTOL operation, initial studies on the annoyance of VTOL type noises, and on general operating experiences with CTOL type aircraft. Much of the technology involved is similar to that described for STOL type vehicles, that is, sources of low frequency noise and specialized operational conditions of longer noise durations, close proximity to urban buildings, etc.

Initial studies of experience with VTOL airline operations have indicated a need for further work to improve the interior environments of the aircraft with special emphasis on the physiological effects of noise/vibration on the crew and the comfort of the aircraft passengers.

For the SST and the HST, the state of the art for noise acceptability in communities near airports is essentially the same as that for large CTOL type aircraft. However, it is noted there may be some exceptions to properly account for different type power plants which could generate noise of different characteristics. The main concern for SST and HST type aircraft is for the sonic boom and its acceptability to those living below its supersonic flight route.

In regard to community acceptance of general aviation aircraft the state of the art is limited to experiences of relatively few airports having noise problems of heavy traffic of the general aviation type. An example is the Orange County, California, airport. Compared to CTOL operations the concern is for low powered aircraft (jet and reciprocating engines) and for non-scheduled operations involving a mix of aircraft types in the airport operations. Information on problems of this type is limited to studies supported by local groups who are primarily concerned with noise regulatory activities.

The interior noise environment of general aviation type aircraft is recognized as requiring attention. The successful growth of general aviation activity has been made with little attention to the adverse effects of the interior noise on the hearing of the aircraft occupants. Initial studies have been begun to obtain some assessment of the severity of hearing threshold losses experienced by some of today's general aviation aircraft. These studies may point the way for more extensive research to lower interior noise/vibration levels to obtain a more acceptable quality of ride in many general aviation type aircraft.

8 Human Response

8.1 Noise measurement unit evaluation

8.2 Subjective evaluation of proposed nacelle retrofit

8.3 Effect of noise on sleep

8.4 Sociometric surveys

8.5 Evaluation of low frequency noise

8.6 Effect of combined in-flight noise and vibration

8.7 Threshold sleep studies

CHAPTER 5

CONCLUDING REMARKS

Aircraft noise alleviation is a complex problem involving not only the technical aspects of reducing noise at the source, but such factors as whole community affairs involving land use, regulations, curfews, safety, and scheduling of aircraft. In addition, it involves such problems of the magnitude of the development of new aircraft systems, such as the SST, human response, economics, environment, etc.

In this document we have attempted to summarize some of the important aspects of noise alleviation, discussing the more important theories, reviewed the state of the art and indicated the critical areas in each technology subgroup which need further research. In summary form,, the critical issues for each subgroup are given below.

Jet Exhaust Noise

(1) Fundamental research on the origin, location, and type of noise source in jet flow.

(2) Propagation path

(3) Noise suppression technology

Airflow-Surface Interaction

(1) Airfoil surface pressure fluctuations

(2) Impingement pressure fluctuation

(3) Prediction of far field noise

Rotating Blades

(1) Determination of sou: ce and magnitude of fluctating blade loads

(2) Vortex interaction

(3) Development of blade geometry for low noise

Sonic Boom

(1) Definition of acceptable exposure

(2) Aircraft configuration for minimum boom

(3) Prediction of focus pressure

Duct Acoustics

(1) Acoustic properties of acoustic liners

(2) Duct propagation prediction techniques

Propagation &Operation

(1) Atmospheric effects on noise propagation

(2) Noise abatement flight procedures

Structural Response

(1) Definition of acoustic loads

(2) Prediction of response of structures

Human Response

(1) Noise measurement unit

(2) Characteristics of people

(3) Low frequency effects on people

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